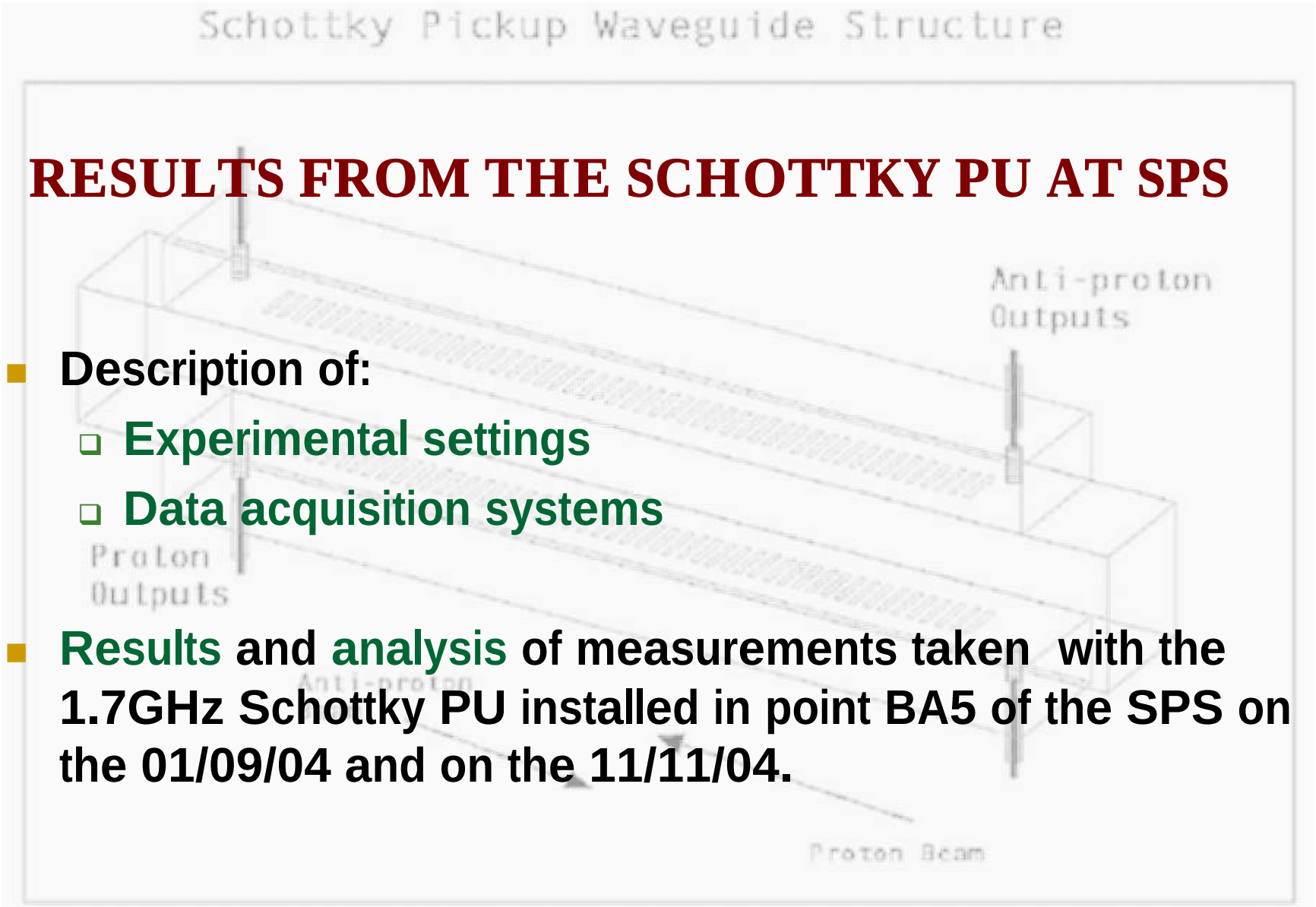
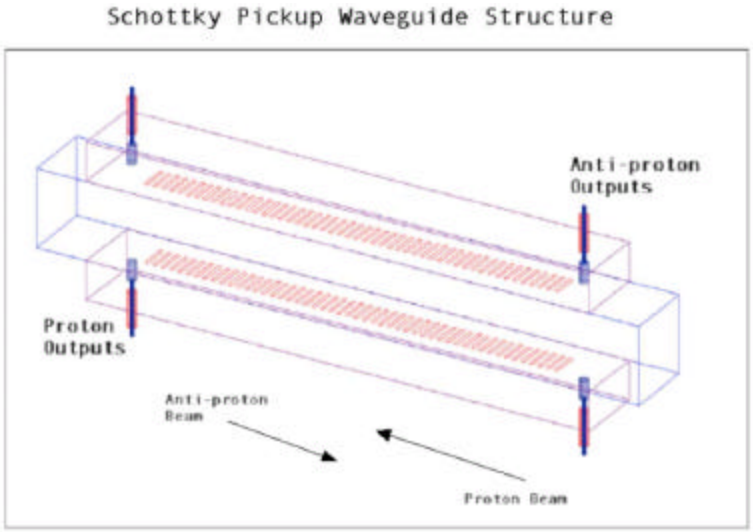
RESULTS FROM THE SCHOTTKY PU AT SPS

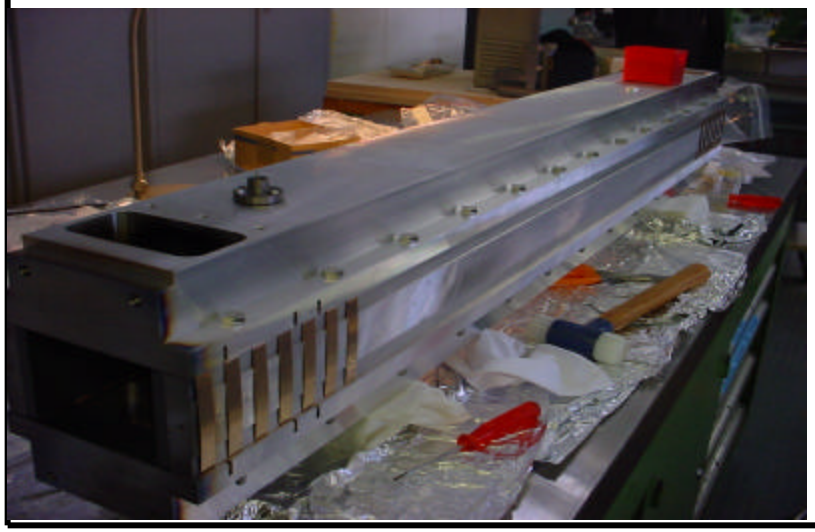
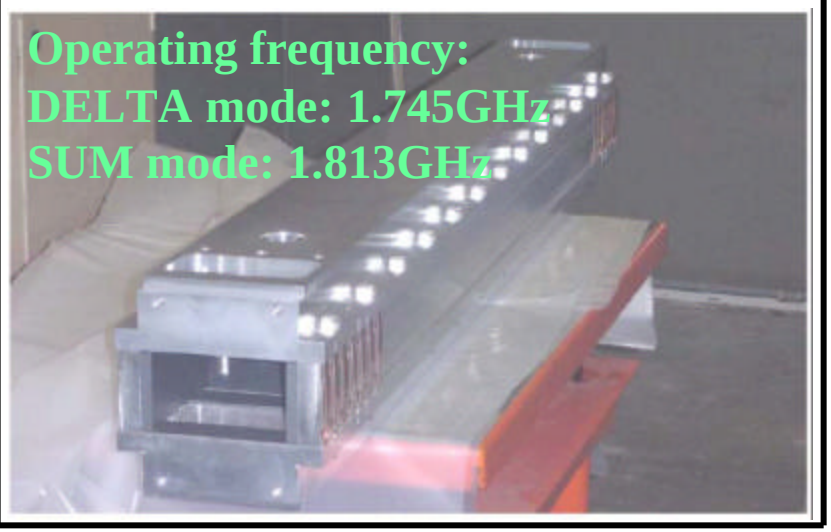


- Description of:
  - Experimental settings
  - Data acquisition systems
- Results and analysis of measurements taken with the 1.7GHz Schottky PU installed in point BA5 of the SPS on the 01/09/04 and on the 11/11/04.

1- Schottky Pickup at SPS

- Same one as in Tevatron and Recycler acc.
- Rectangular beam pipe and slotted waveguide on top and bottom.
- Designed to measure betatron sidebands and transverse Schottky signals.
- SPS: Operating freq @ 1.803GHz, multiple of ~200MHz and 40MHz beam.



Schottky PU at CERN	1.7GHz Schottky PU at FNAL (*)
	

(*): “A 1.7 GHz Waveguide Schottky Detector System”, R. Pasquinelli.

2- First measurements. Experimental setting

2.1- Measurement of the amplitude of signal being received from tunnel (6/25/04). Delta signal minimization (attenuators):

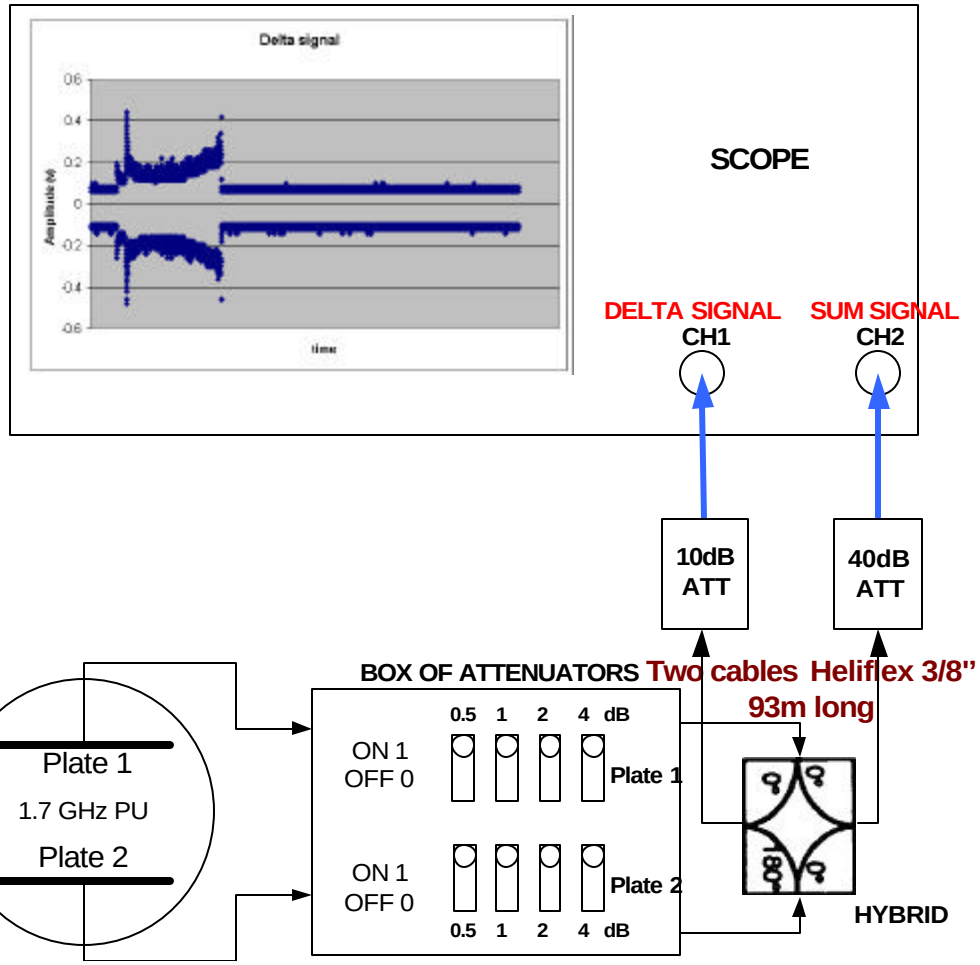


TABLE 1: LEVEL BEING RECEIVED FROM TUNNEL

Signal	Vpeak (on scope)	Attenuators at input of scope	Vinput (before attenuation)
D	440mV	10dB	~1.4V
S	146mV	40dB	~14.6V

~12 dB att of coax cable @ ~1.8GHz

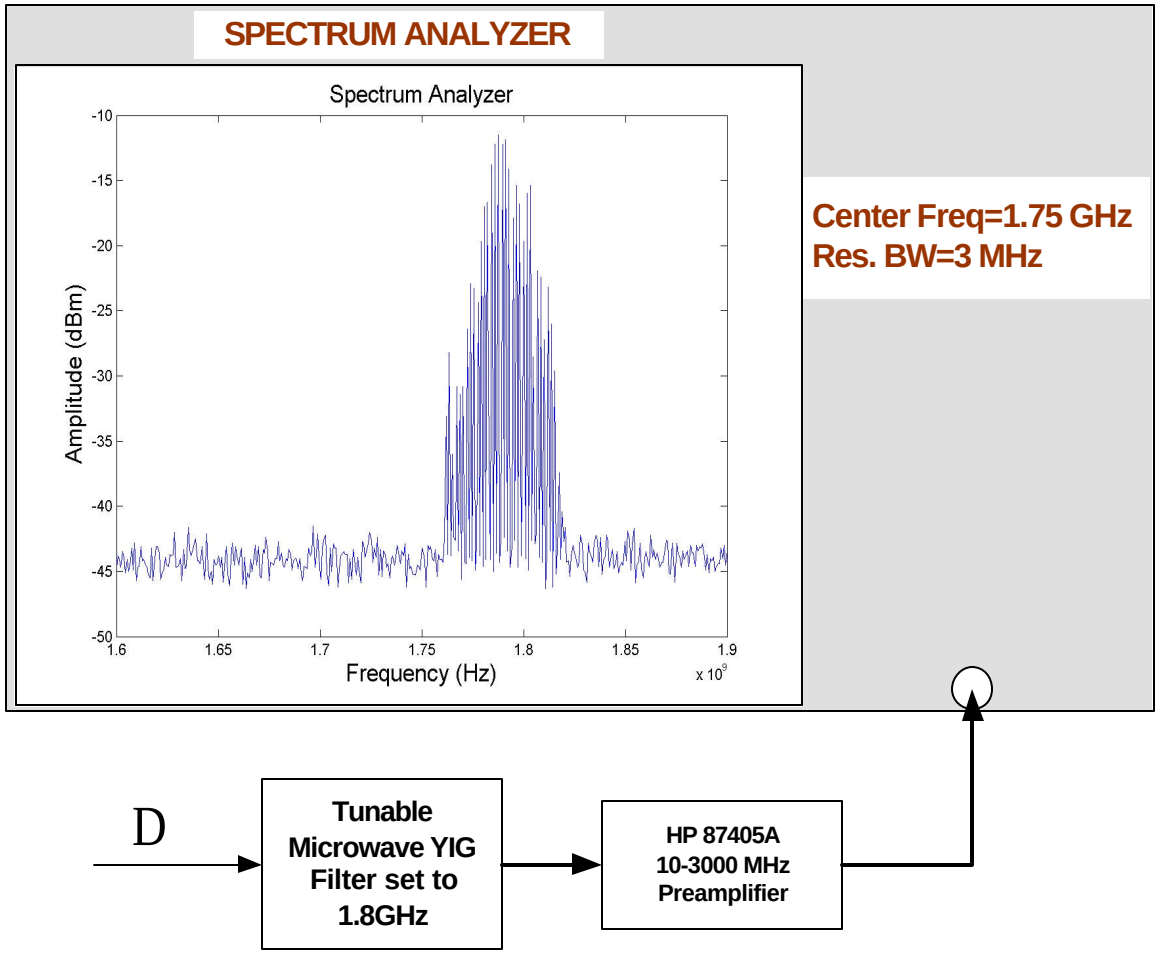
SIGNAL LEVEL AT OUTPUT OF HYBRID

$V_{delta\ peak} = \sim 5\ V$

$V_{sum\ peak} = \sim 51\ V$

2.2-First measured response in frequency domain (7/1/04):

- Input SPA ➔ Delta signal.
- Center Freq. in SPA set to 1.75GHz.
- Tunable YIG filter in surface @ 1.8GHz to reduce peak signal amplitude at preamp input.
- Preamplifier.
- Spectrum shows essentially the response of the YIG filter.



3- Results from measurements taken in BA5 on the Schottky PU (9/1/04)

- Data acquisition with:
  - FFT analyzer
  - Spectrum analyzer (SPA)

The employment of both devices was intended to show the consistency of results.

- By means of a hybrid we obtain Sum and Delta signals from the Schottky PU arms:
  - Measurements using the Sum signal➔longitudinal sensitivity of the PU.
  - Measurements on the Delta signal➔ transverse spectrum.

- Most measurements were taken with the combination of attenuators that minimizes the signal of the revolution harmonics (adjustment of electrical center of PU to position of the beam).
- Connection of a passive 1.8GHz BPF and low noise preamp to output of hybrid for Delta signal in the tunnel (S/N ratio!).

3.1- Cycle and Beam settings in the SPS on Wednesday 09/1/04 (10:00-13:00)

- **Bunched beam in coast.**
- **LHC beam with 40MHz structure: 72 bunches spaced by 25 ns.**
- **Vertical fractional tune $q_v \sim 0.19$**

	UNITS	SPS
Coast beam Energy	GeV	26
Momentum	GeV/c	26
Revolution Frequency	kHz	43.347
Betatron Tune, QH		26.13
Betatron Tune, QV		26.19
Intensity per bunch		$1.3*10^{+11}$
Number of bunches		72
Number of batches		Up to 2
Bunch Spacing	ns	25
Bunch Length	ns	4
Normalized r.m.s Vertical Emittance (ε^*v)	μm	~3.5-3.6
$\Delta p/p$ (r.m.s.)		1×10^{-3}
Beam r.m.s radius (a_{rms})	mm	1.8
(Main) RF Frequency	MHz	200
SPS γ_{tr}		23.4
SPS circumference (C)	m	6911.560387

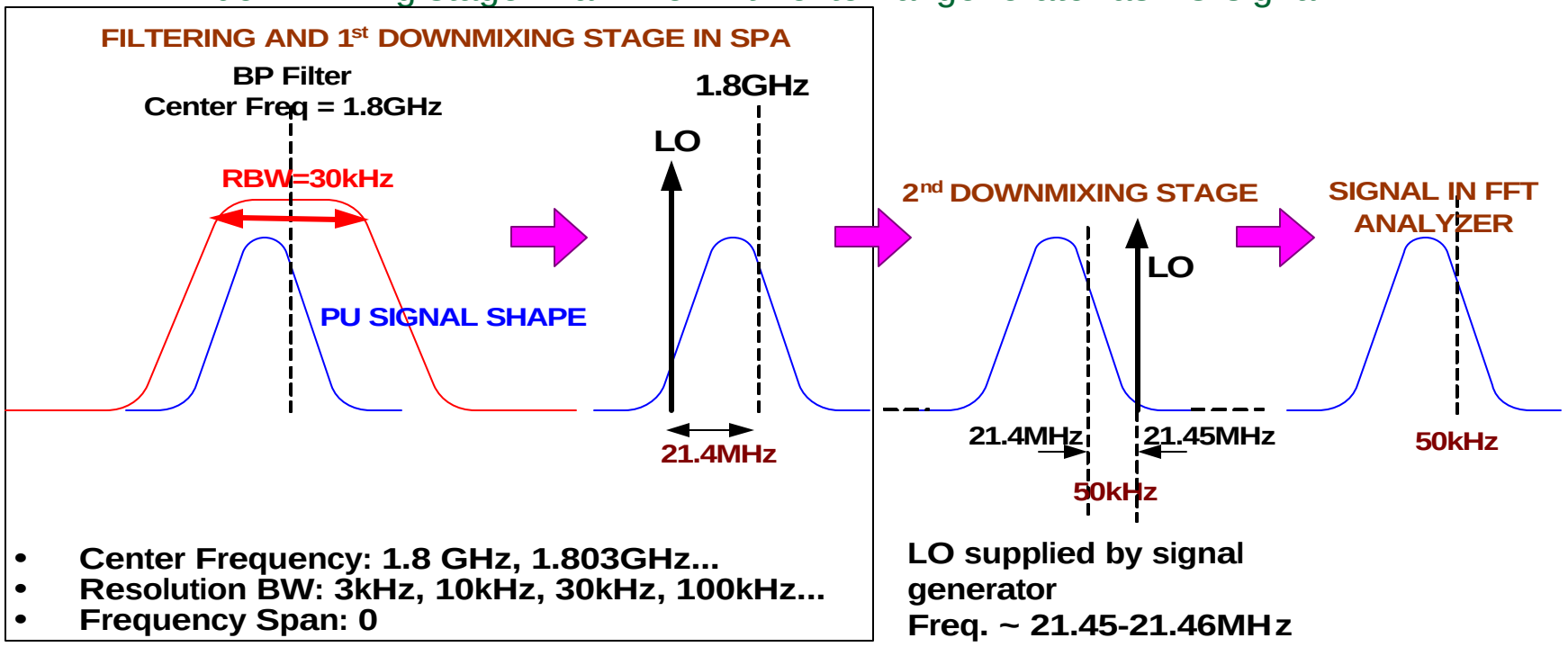
3.2- Measurement systems in BA5 and results:

Measurements on the SR785 FFT Analyzer:

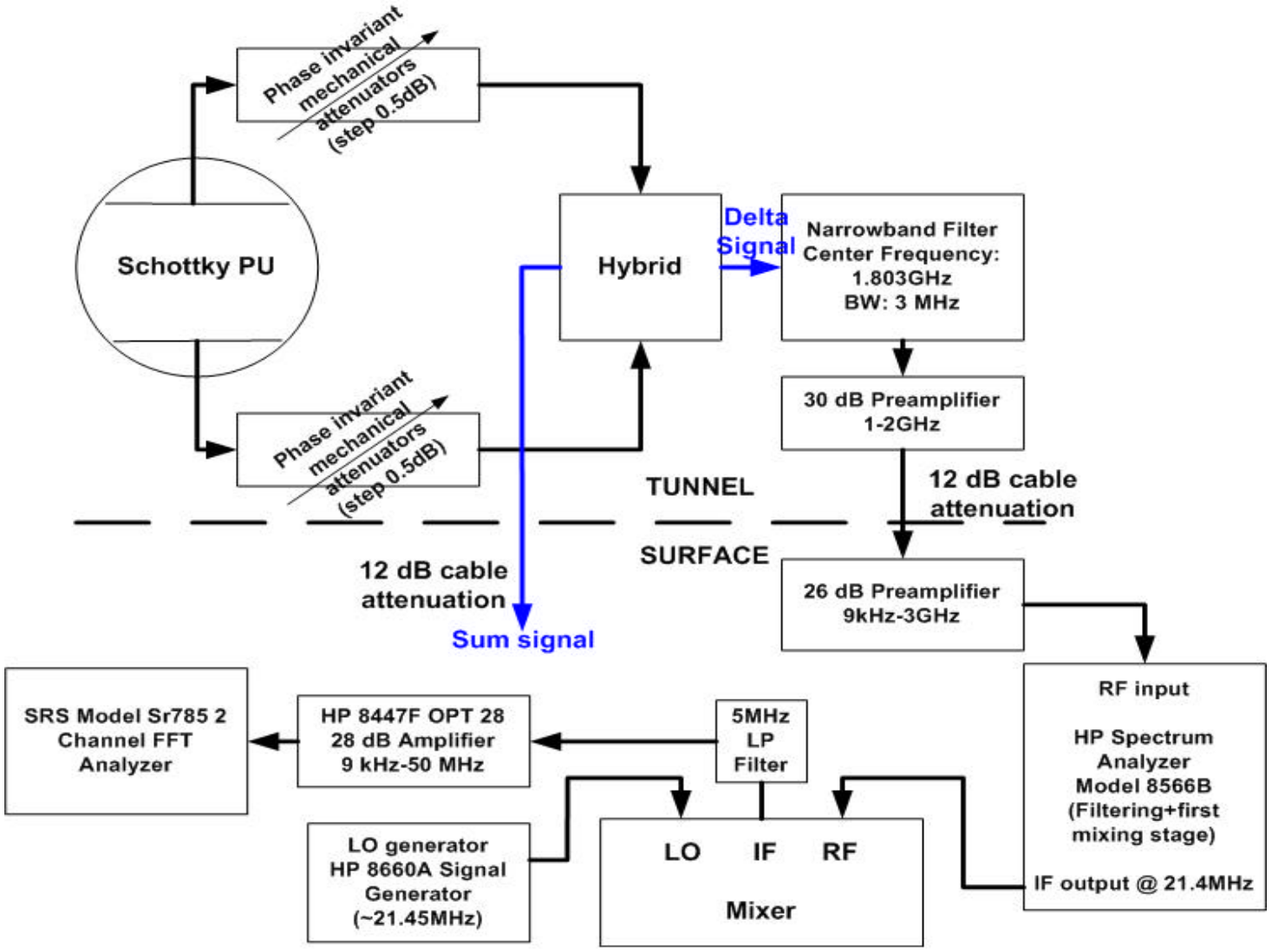
- FFT analyzer used for transversal scans on Delta signal.
- Frequency range: from 195.3 mHz to 102kHz ➔ downmixing of Delta signal required.

Downmixing process:

- One filtering and two downmixing stages:
  - Filtering in HP 8566B SPA:
  - 1st downmixing stage in HP 8566B SPA:
  - 2nd downmixing stage in a mixer with external generator as LO signal.



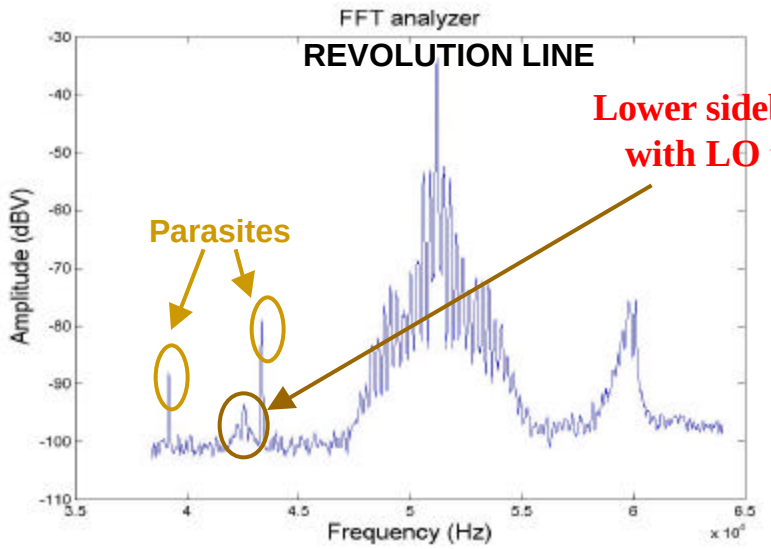
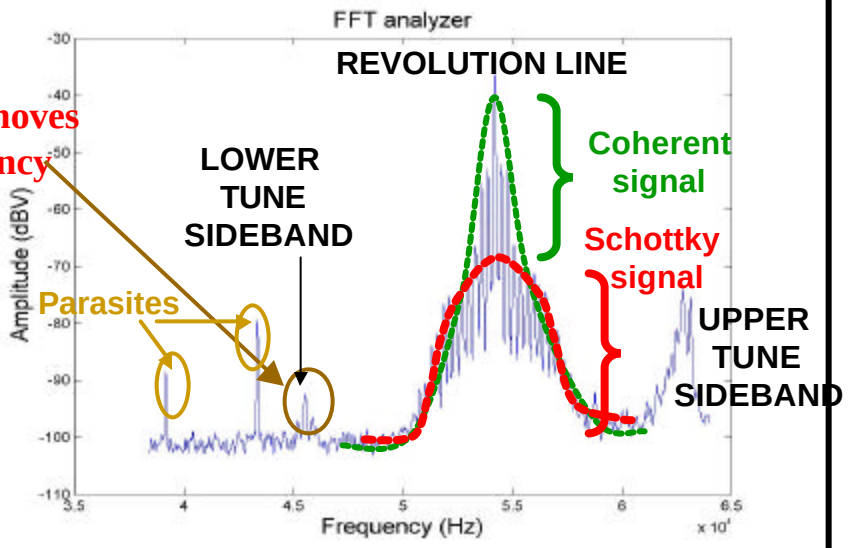
Schematic diagram of experimental setting:



Some results for transverse spectrum:

- **Revolution lines (beam not centered in the detector).**
- **Two sidebands** associated to betatron oscillation.
- **Spurious lines** near lower tune sideband: change in LO frequency moves the whole spectrum to the right with the exception of the noisy peaks.

Notes: The frequency span is 30kHz.

File: coast43.txt, time 12:46pm HP 8566B SPA: Center Freq: 1.803GHz, BW:10kHz LO Frequency: 21.4632MHz, Switches: 1000 1000	File: coast44.txt, time 12:48pm HP 8566B SPA: Center Freq: 1.803GHz, BW:10kHz LO Frequency: 21.4662MHz, Switches: 1000 1000
	

A bit of Schottky theory…

SCHOTTKY SIGNALS:

- **To obtain diagnostic information on a particle beam without perturbing it.**
- **Unbunched beam, longitudinal:**

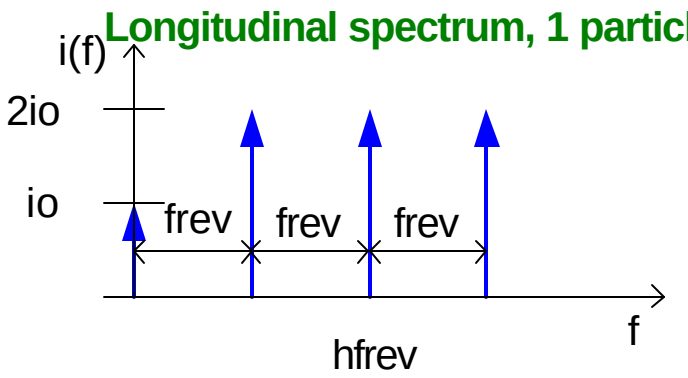
Single particle circulating around the machine ➔ Beam current at a given location:

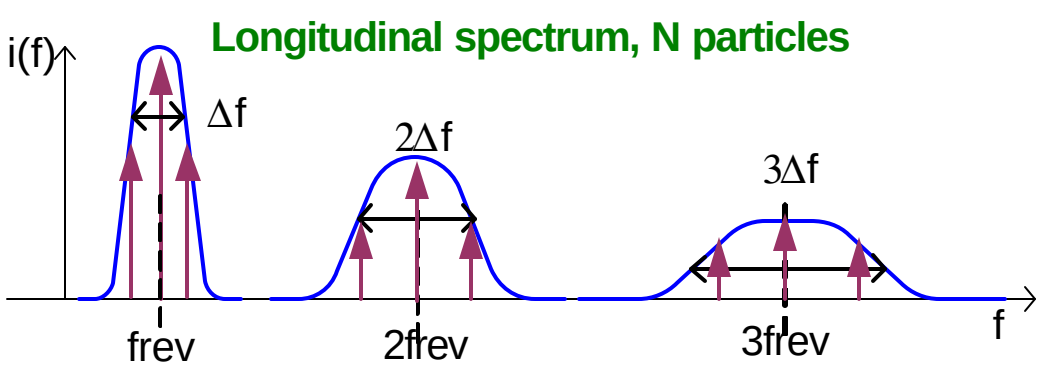
$$i(t) = i_o + 2i_o \cos(2\pi f_{rev} t) + 2i_o \cos(4\pi f_{rev} t) + \ldots$$

For N particles having slightly different energy (frev) ➔ line is replaced by a band of frequencies of width:

$$\Delta f = h f_{rev} \frac{\Delta p}{p}$$

(Δf increases with h)





A bit of Schottky theory… (cont.)

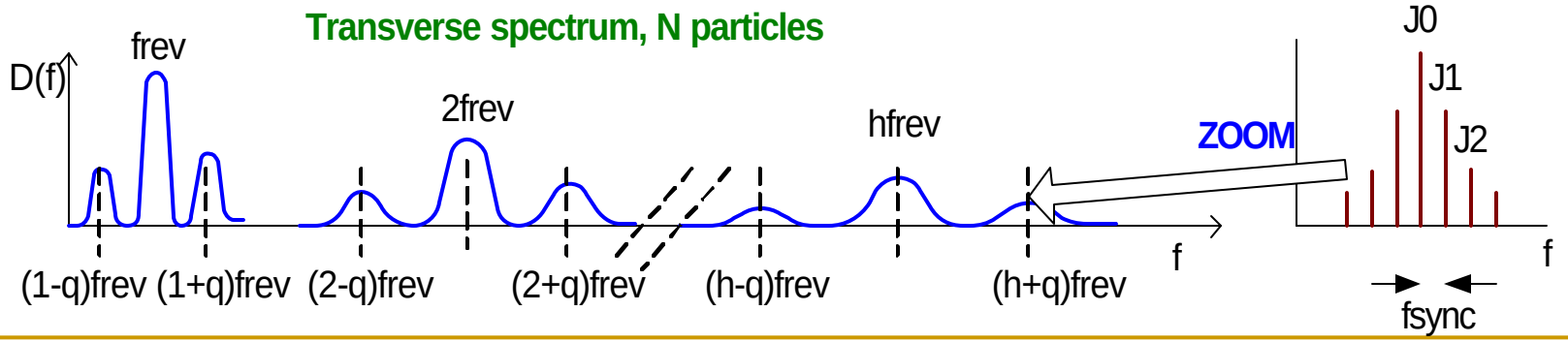
- **Unbunched beam, transversal:** particles execute sinusoidal betatron oscillations. Current is replaced by dipole moment:

$$D(t) = e \cdot a \cdot f_{rev} \cdot \{\cos(2\pi q f_{rev} t + \phi) + \sum_{1}^{\infty} \cos[(n+q)2\pi f_{rev} t + \phi] \cdot \sum_{1}^{\infty} \cos[(n-q)2\pi f_{rev} t + \psi]\}$$

Each revolution frequency line is converted by the amplitude modulation into two lines at a distance $qv \cdot frev$ from rev. line. N particles having different energy lines are replaced by freq. bands:

$$\Delta f_{u,l} = \frac{\Delta p}{p} f_{rev}[(n \pm q)h \pm Qx]$$

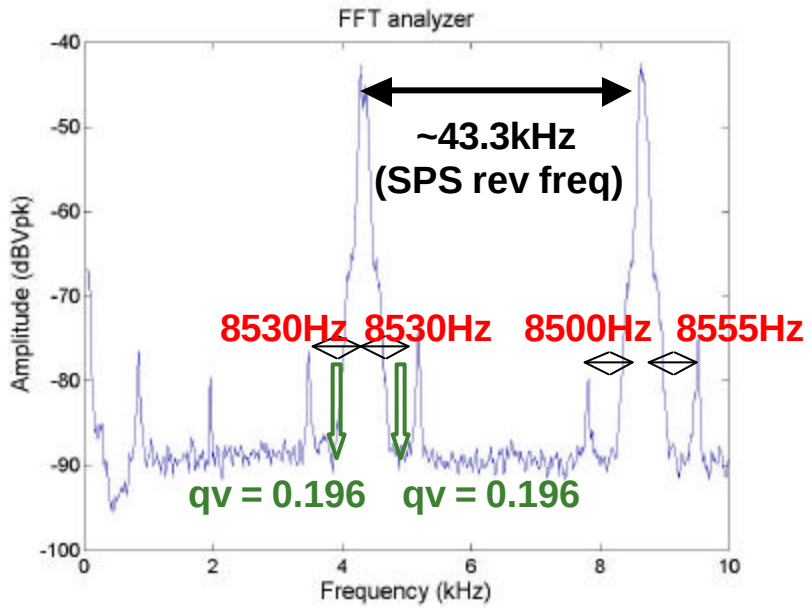
- **Bunched beam transversal:** synchrotron oscillations ➔ rev. line and transverse tune lines split into synchrotron satellites.



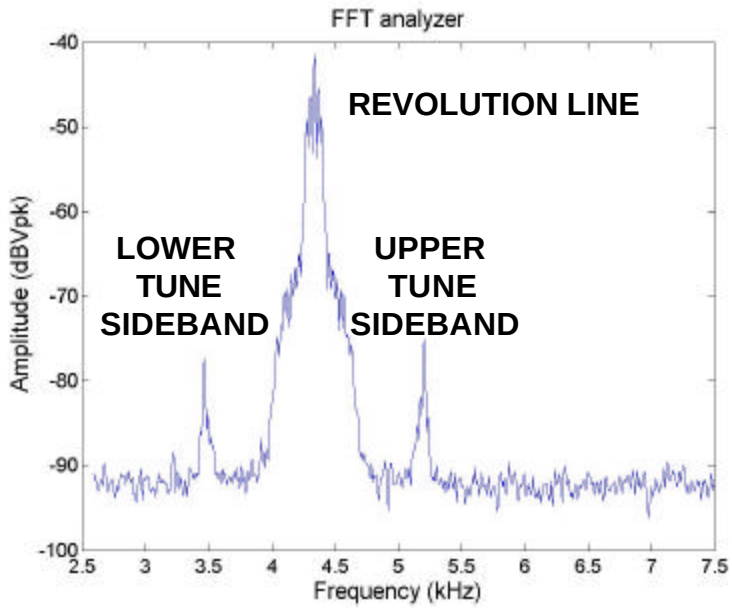
Some other plots with different frequency ranges in the FFT analyzer:

- Revolution lines.
- Betatron sidebands. According to theory @ distance from rev. line: ±0.19*43.3kHz = ±8.227kHz

File: coast48.txt, time 12:57pm
HP 8566B SPA: Center Freq: 1.803GHz, **BW: 100kHz**
LO Frequency: 21.4552MHz, Switches: 1000 1000



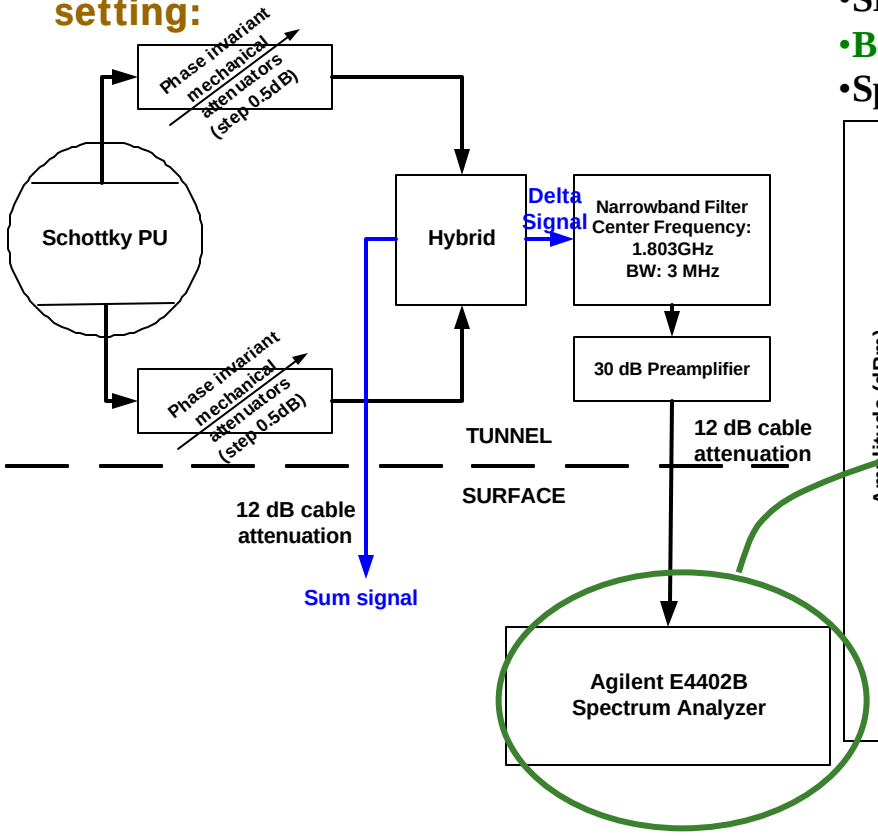
File: coast49.txt, time 12:58pm
HP 8566B SPA: Center Freq: 1.803GHz, **BW: 100kHz**
LO Frequency: 21.4554MHz, Switches: 1000 1000



Measurements on the Agilent E4402B Spectrum Analyzer:

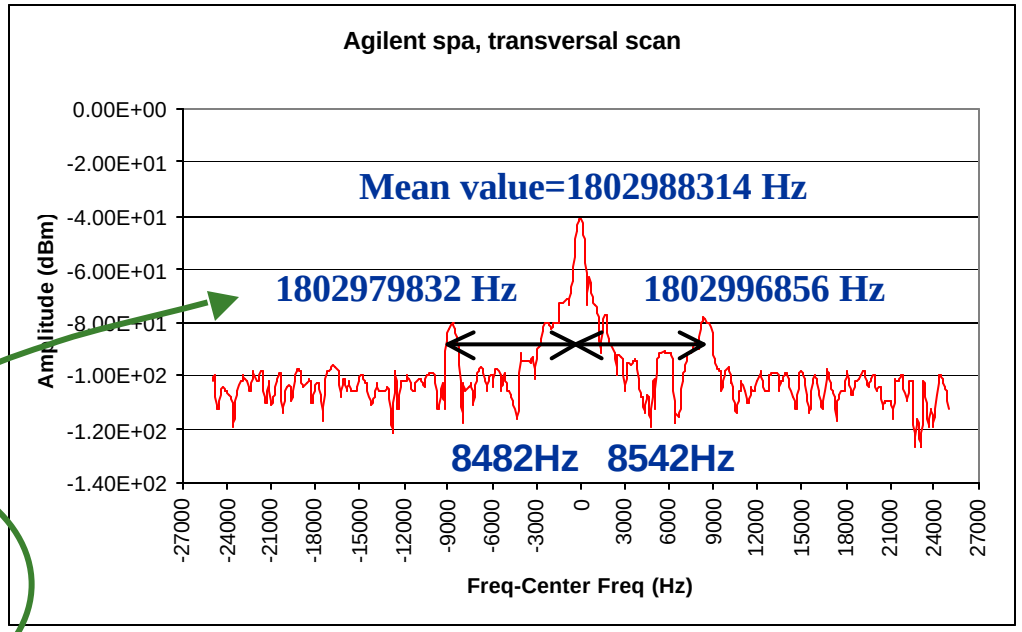
- Transverse scan of bunched beam: comparison between the observed spectrum on the FFT Analyzer and the one observed on the Agilent SPA.

Schematic diagram of experimental setting:



Trace124.csv, time 12:13 pm

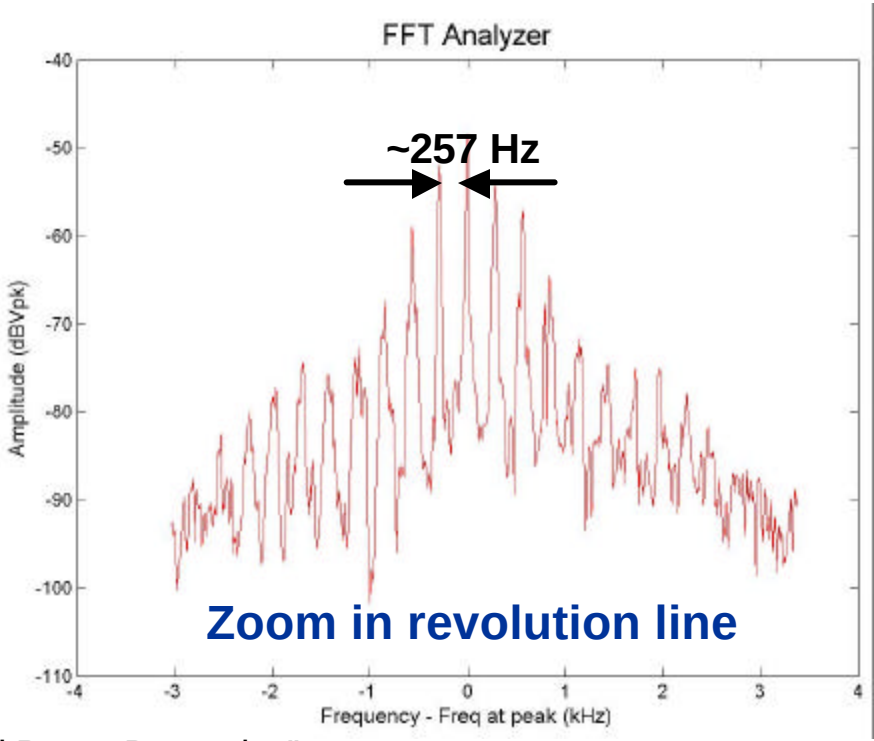
- **SPA center freq = 1802988500 Hz, Resolution BW = 300 Hz**
- **Best filter transmission @ ~1.803GHz**
- **Spectrum consistent with FFT analyzer: revol. line & tune lines**



Tune values:
From upper sideband: 0.195
From lower sideband: 0.197

Transverse scan of bunched beam (cont.)

- Expected spectrum: Revolution line + tune lines split into synchrotron satellites.
- Observed spectrum: Rev. line & tune lines
- Beam in coast at 26 GeV.
- Resolution BW of SPA = 300Hz, FFT much better.
- Synchrotron freq ~ 280Hz. This compares well to the nominal synchrotron frequency of 257 Hz at injection (26GeV)(*).



(*): From LHC Design Report, “RF System and Longitudinal Beam Dynamics”.

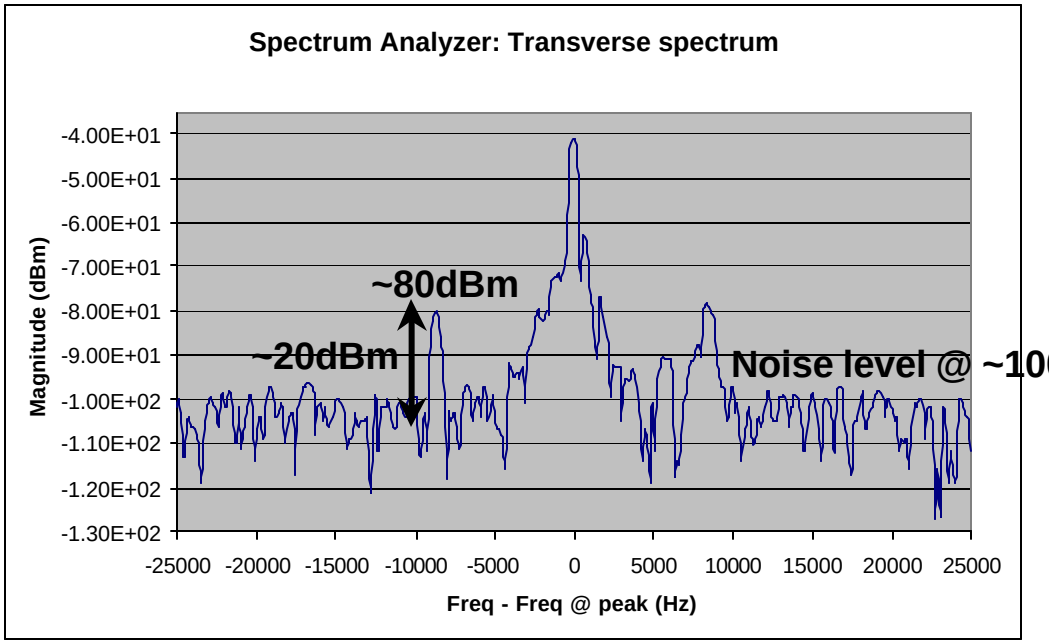
Transverse scan of bunched beam (cont.)

Difference mode impedance for a slow wave pick up:

$$Z_{\Delta} = (g-1)\cdot \frac{N_f \cdot S_{therm}}{2\cdot e\cdot I_{dc}\cdot \left(\frac{s}{d}\right)^2} (*)$$

g = power ratio:

$$g = \frac{P_{beam} - P_{noise}}{P_{noise}}$$

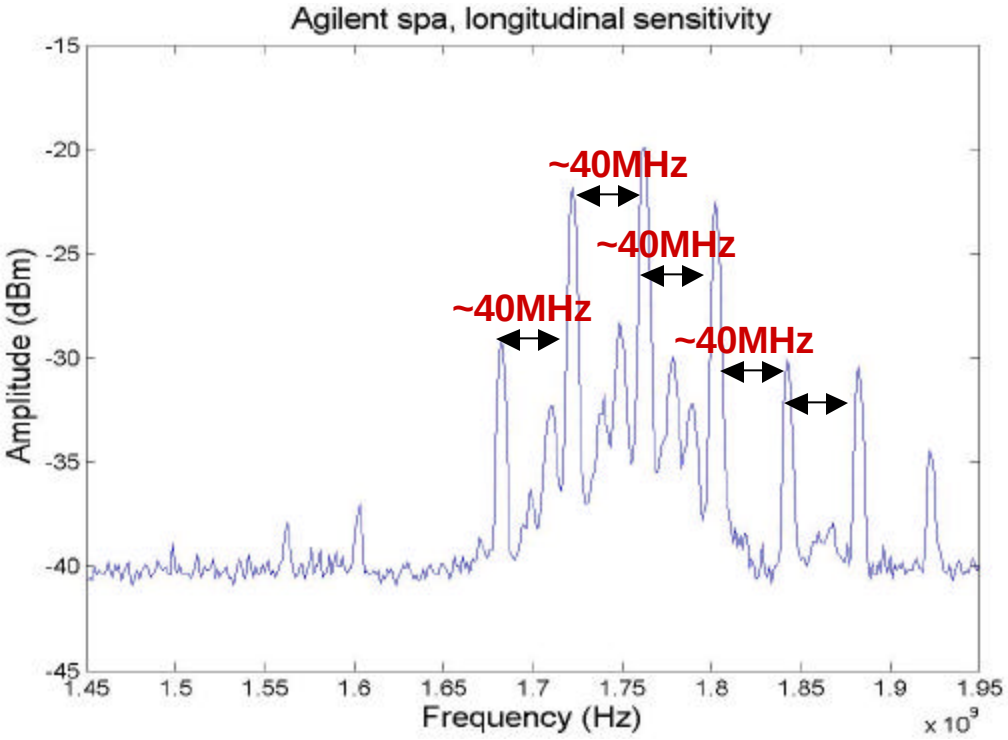


Expected Signal to Noise ratio:

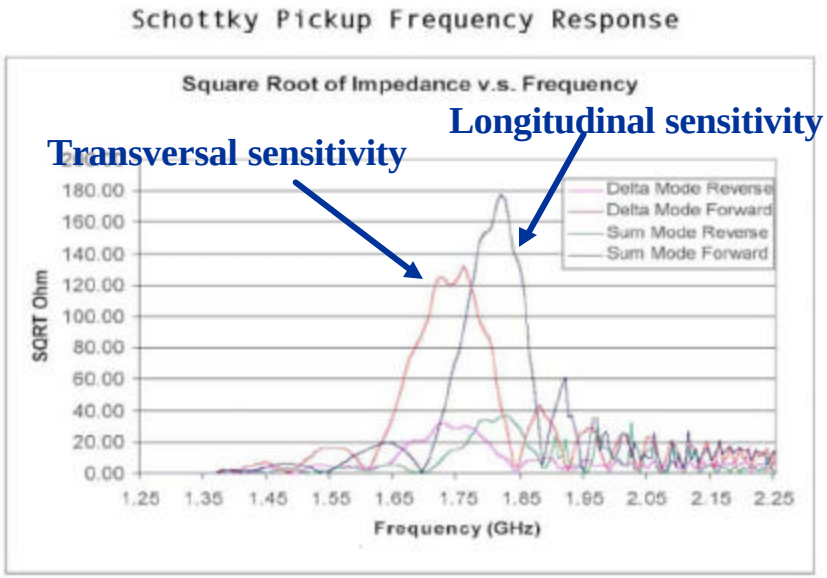
$$S/N = 20\cdot \log\left(\frac{I_{beam}}{I_{noise}}\right) = 20\cdot \log\left(\frac{5.62\cdot 10^{-11}}{8.9\cdot 10^{-12}}\right) = 16dB$$

(*): From “Slotted Waveguide Slow-Wave Stochastic Cooling Arrays”, D. McGinnis, FNAL, Batavia, IL and from “Pbar Note 624: Accumulator 4-8 GHz Cooling Pickups Impedance Measurements”, Paul Derwent.

- Longitudinal sensitivity profile of the Schottky PU ➔Sum (Σ) signal.
- Spectrum analyzer with 40 dB attenuator and RF limiter before the input of SPA.
- Distance between adjacent peaks = 40MHz➔shows expected LHC beam structure.
- Best response of the PU around 1.7625 GHz.



Schottky PU at CERN



1.7GHz Schottky PU at FNAL

Freq spectrum induced by bunched beam moves PU max response to lower frequencies

4- Results from measurements taken in BA5 on the Schottky PU (11/11/04)

4.1- Cycle and Beam settings in the SPS on Thursday 11/11/04 (8:00–16:00)

- **Beam conditions:**

LHC in SPS on SC 950

- **Bunched beam in coast.**
- **LHC beam with 40MHz structure.**
- **Vertical fractional tune 0.175**

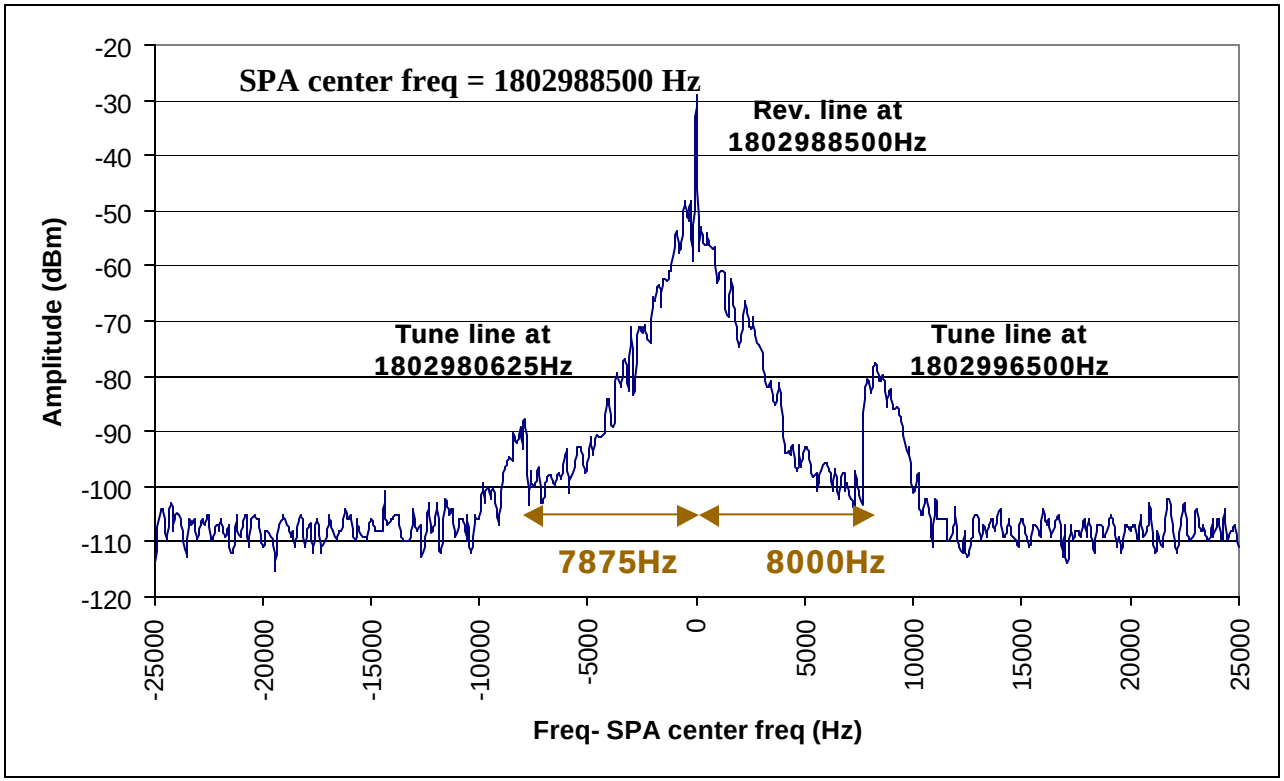
	UNITS	SPS
Coast beam Energy	GeV	26
Momentum	GeV/c	26
Revolution Frequency	kHz	43.347
Betatron Tune, qv		0.175
Intensity per bunch		$1.3*10^{+11}$
Number of bunches		72
Number of batches		Up to 2
Bunch Spacing	ns	25
Bunch Length	ns	4
Longitudinal Emittance (ε_L)	eV·s	0.35
Transverse Normalized Emittance in both planes (ε_{H,V^*})	μm	~3
Δp/p (r.m.s.)		1×10^{-3}
Average Beam Size radius	mm	1.8
(Main) RF Frequency	MHz	200
SPS γ_{tr}		23.4
SPS circumference (C)	m	6911.560387

4.2- Measurement systems in BA5 and results:

Measurements on the Agilent E4402B Spectrum Analyzer:

- **Transverse scan:** PU response: Center Freq. = 1802988500 Hz, Res. BW = 30 Hz, effective RBW becomes 125Hz due to limited number of points on screen (401)==> no synchrotron lines visible.

Trace586.csv, time 12:13pm



Fractional tune values:

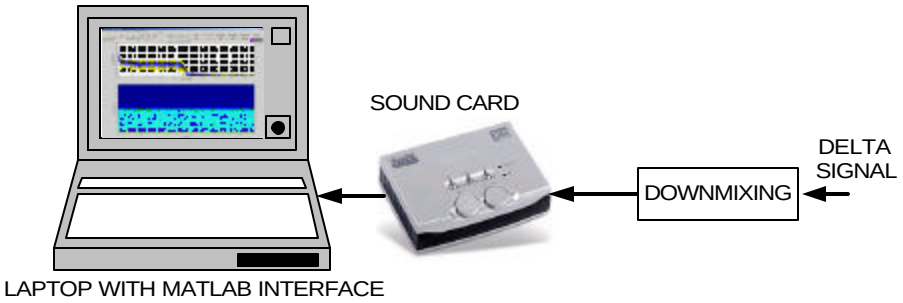
•From lower tune sideband ➔ qv=0.181

•From upper tune sideband ➔ qv=0.184

(qv=0.175 given by control room)

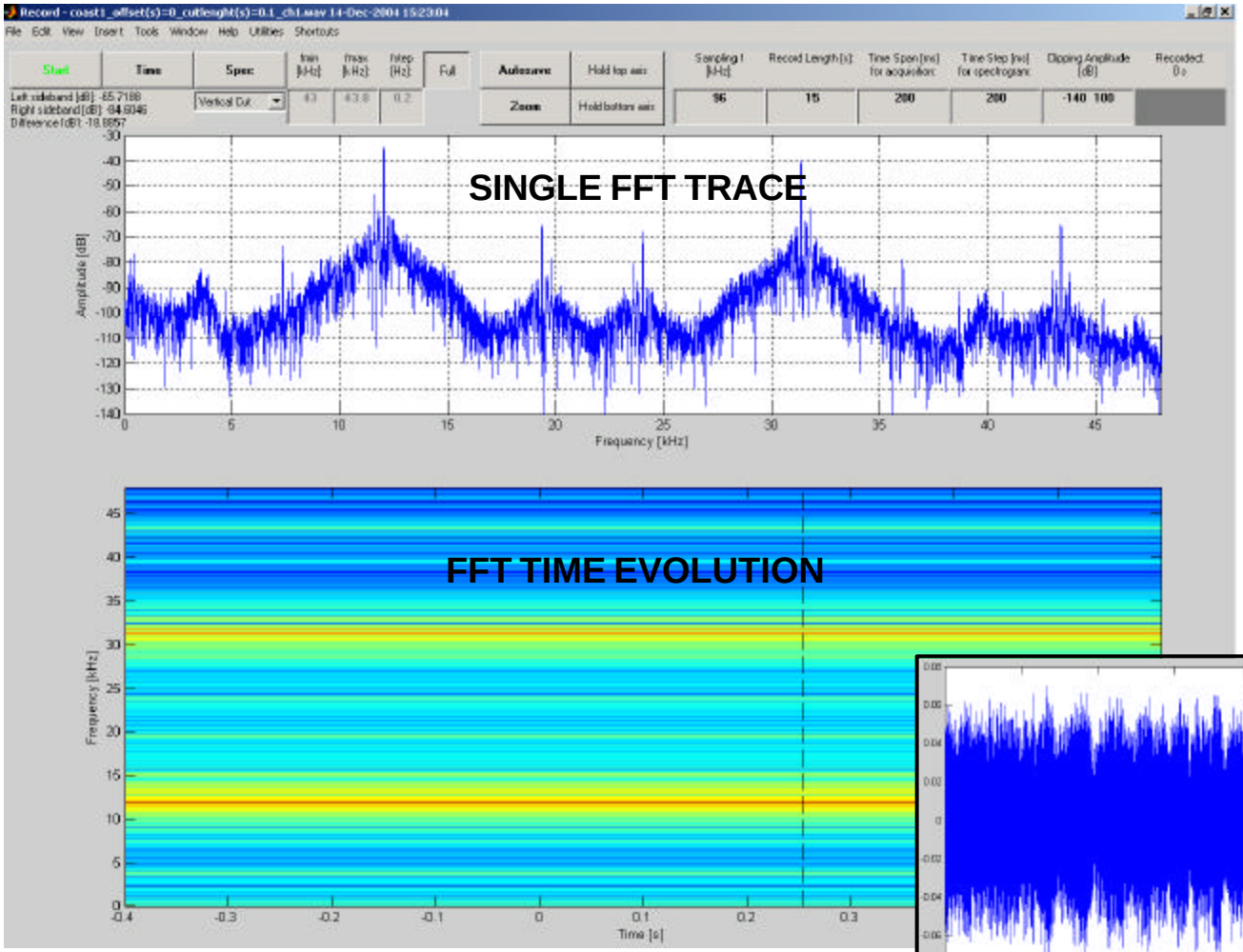
Data taken with sound card:

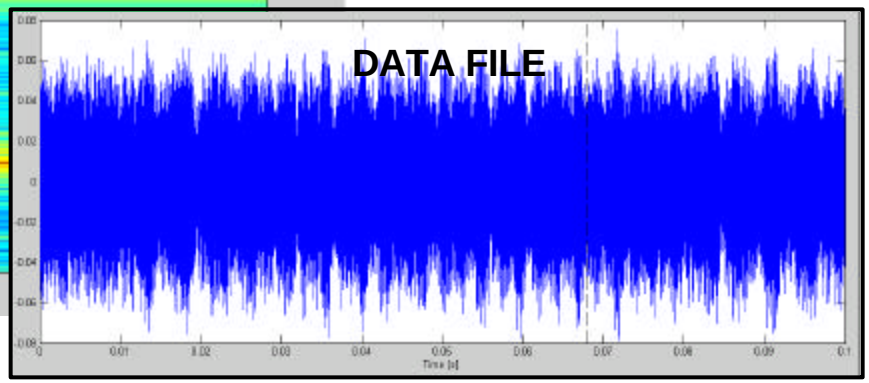
- **New acquisition system** (idea from Marek Gasior):
  - USB external sound card (Sound Blaster Audigy2 NX, 24bit, 96kS/s):
  - Laptop
  - Matlab interface (Tom Kroyer).



	SOUND CARD	FFT ANALYZER
SAMPLING FREQUENCY	96 kHz	262.1kHz
FREQ RANGE	~20Hz-48kHz	~0Hz-102kHz
DATA STORAGE	Fast storage of big amount data limited by laptop memory.	Data storage limited by internal FFT buffers. Data transfer for analysis is a slow process and device remains no operational.
LO FREQ	~21.41MHz	~21.45-21.46MHz

- **Software for acquisition:** Matlab program running in laptop connected to sound card (Tom Kroyer).

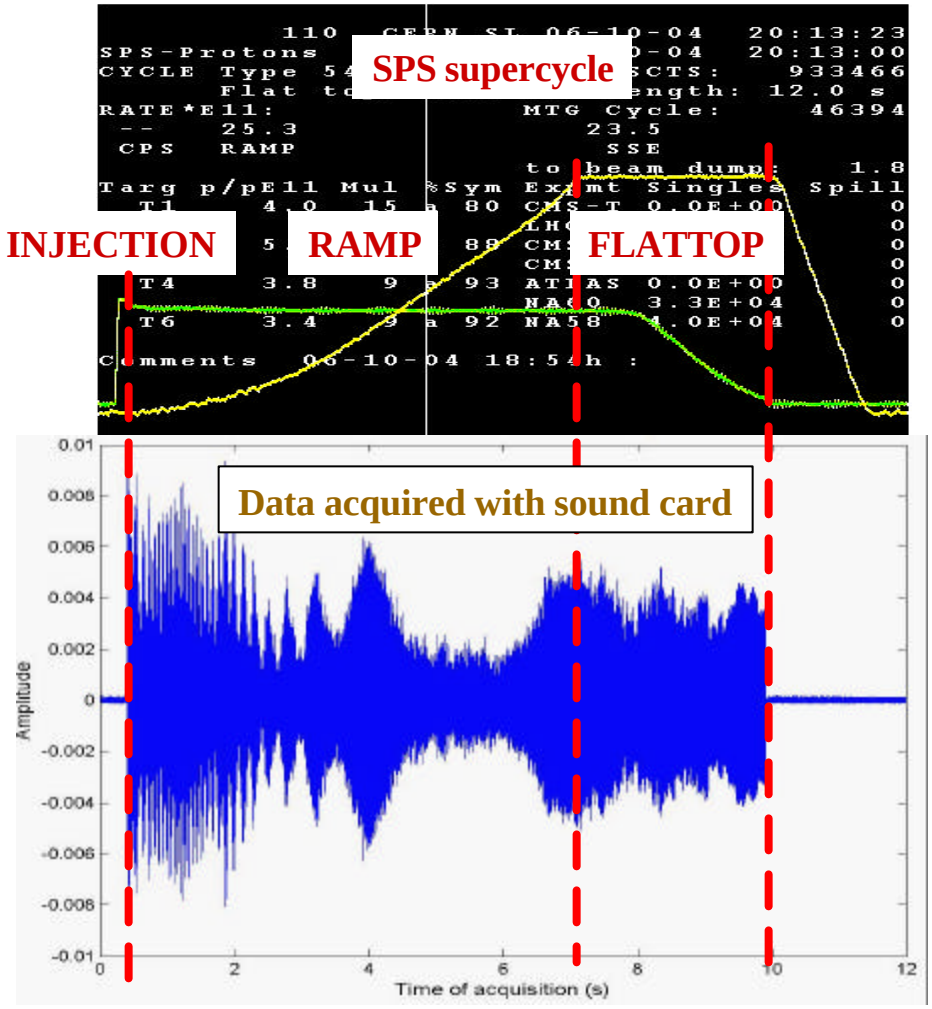




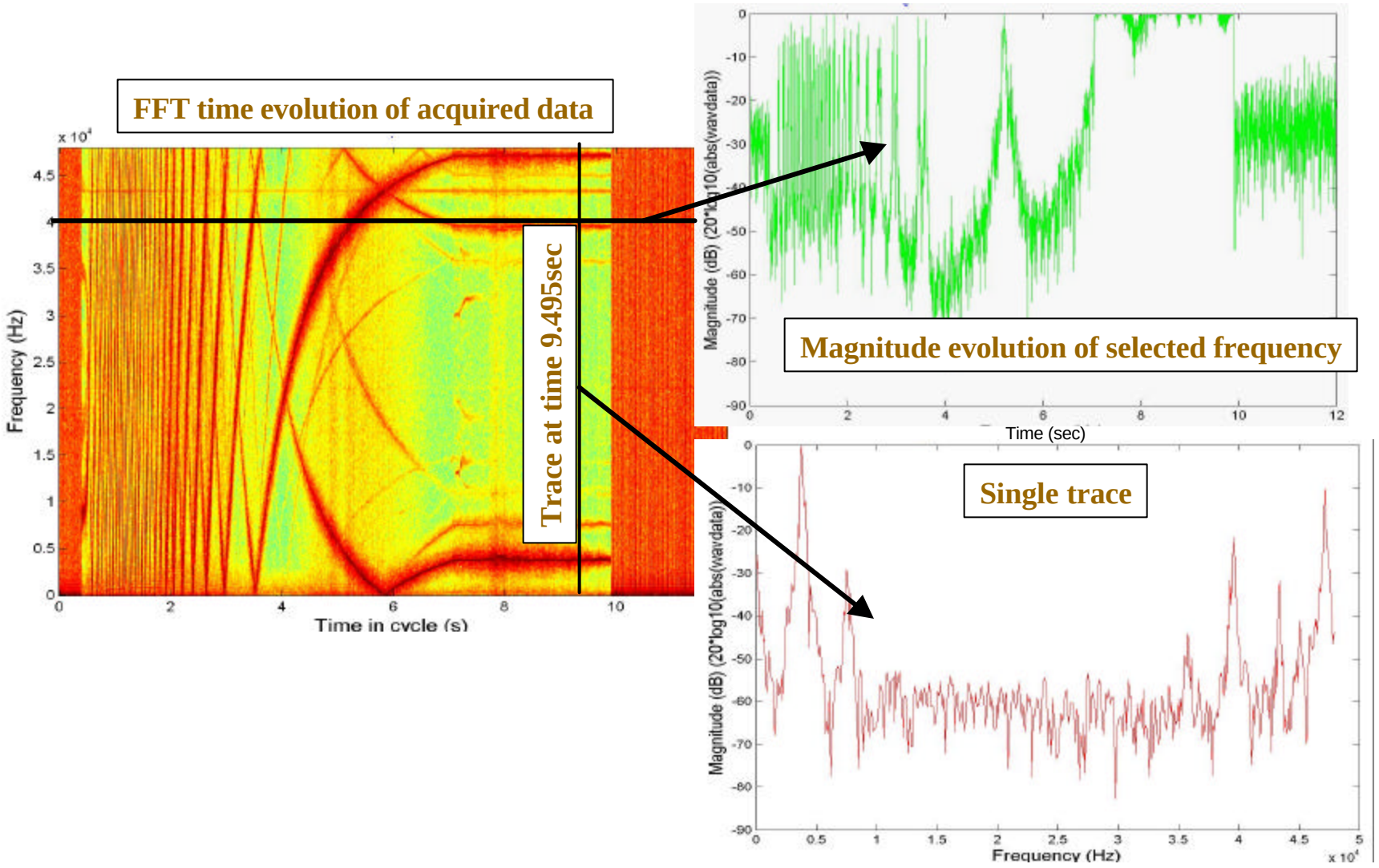
- Continuous data acquisition
- Possibility of data storage
- FFT of data

Example of data acquisition and data analysis :

- Data acquired on 11/10/2004 (qv = 0.757)
- Matlab program for FFT transforms.

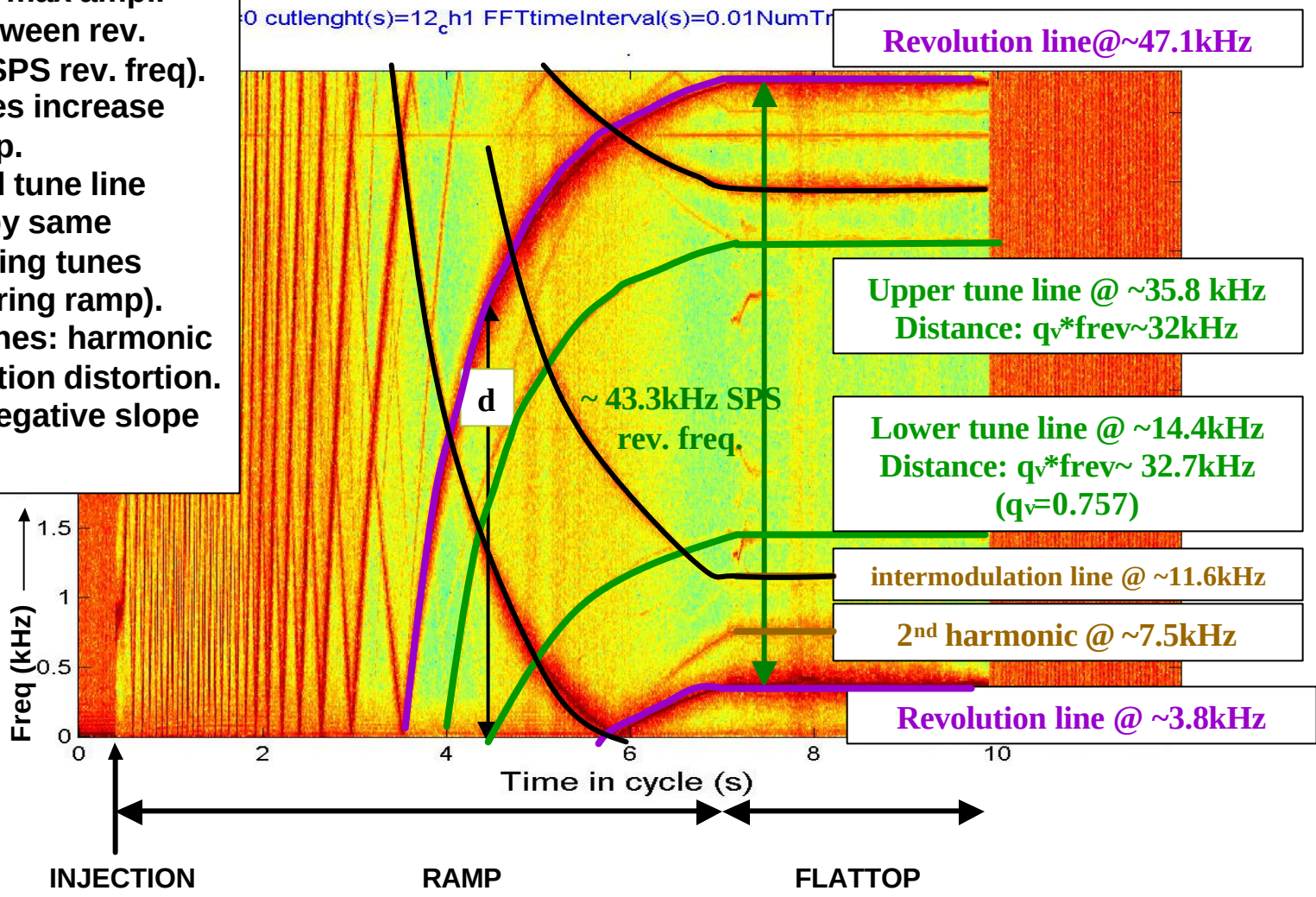


Example of data acquisition and data analysis (cont.):



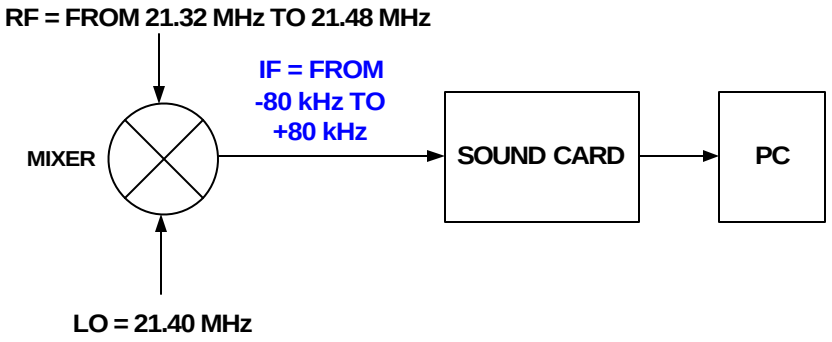
Criteria for signal recognition in dynamic situation:

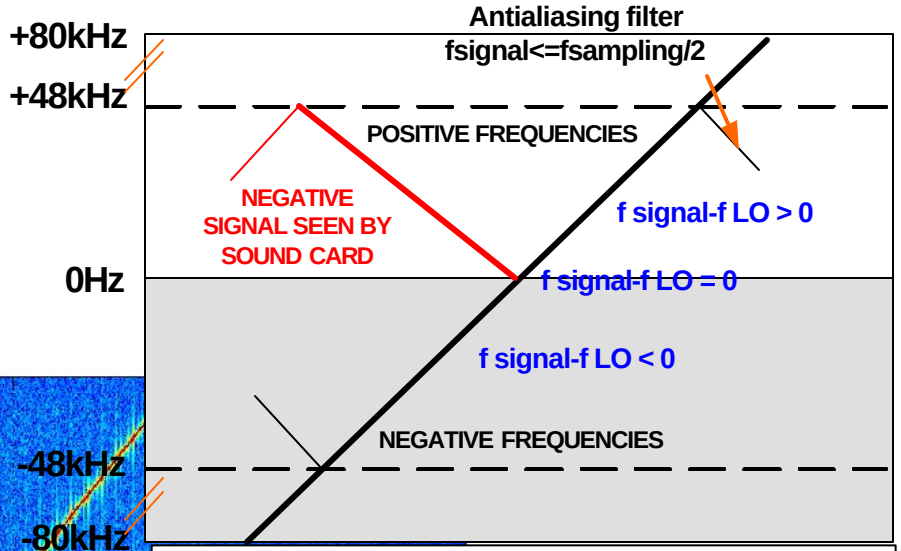
- Rev. lines @ max ampl.
- Distance between rev. lines »43.3kHz (SPS rev. freq).
- Real rev. lines increase freq. during ramp.
- Rev. line and tune line always spaced by same distance (assuming tunes not changing during ramp).
- Additional lines: harmonic and intermodulation distortion.
- Lines with negative slope are images.

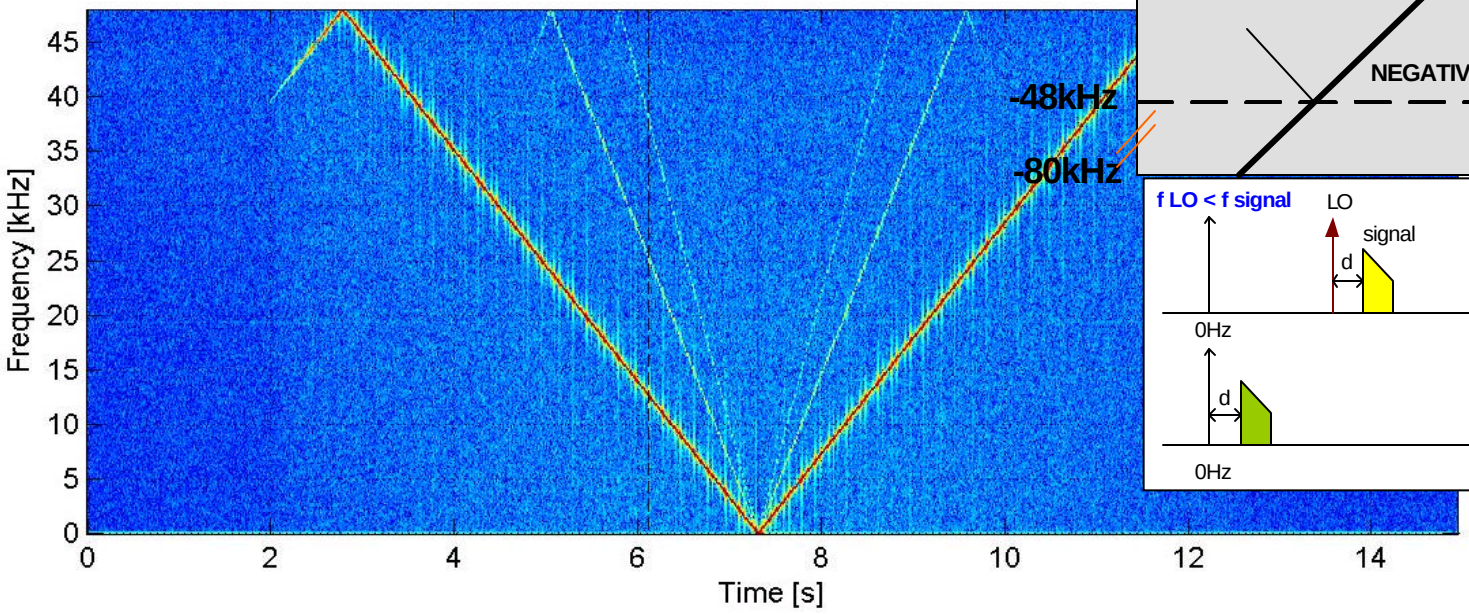


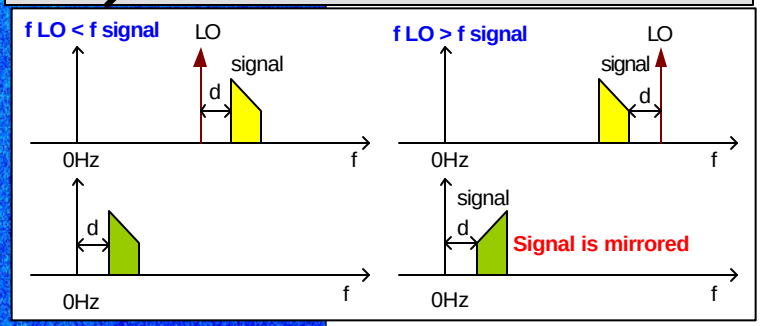
Explanation of signals with negative slope :

They are negative signals resulting from downmixing process when $f_{signal} < f_{LO}$ and that are mirrored and seen by sound card.





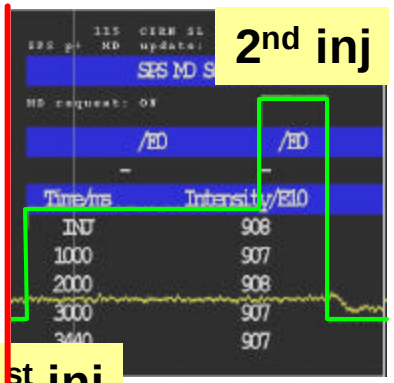


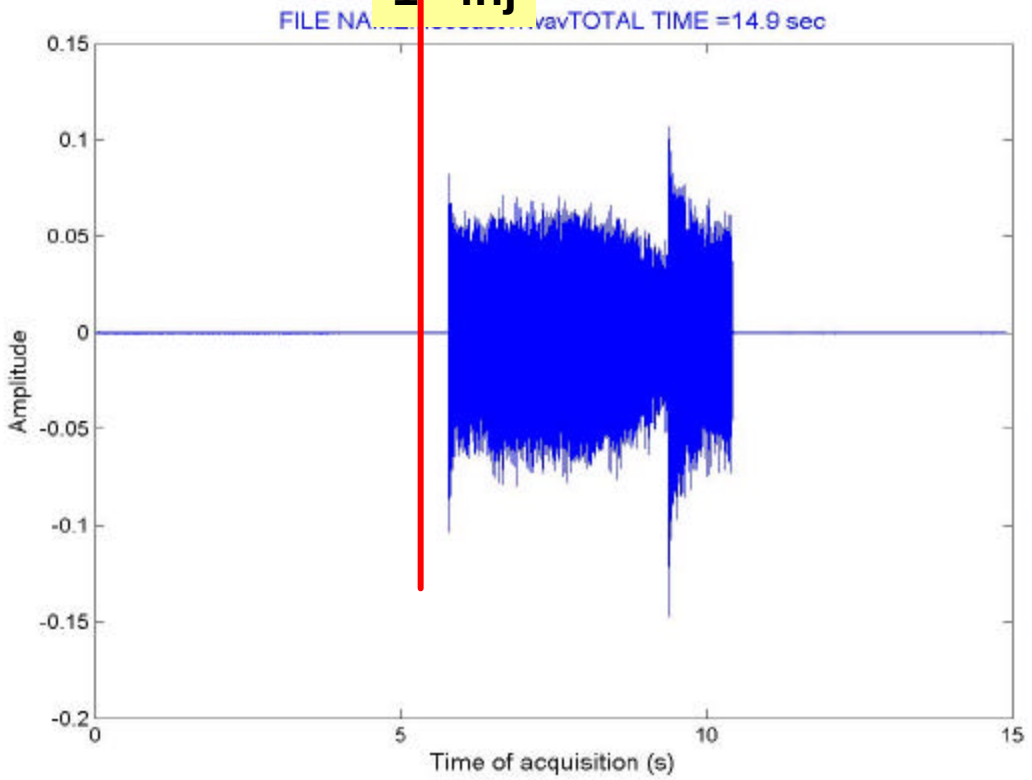


Data acquired on 11/11/2004 :

- 26GeV flat bottom, 2 injections
- Acquired data:
  - 14.9 seconds of data.
  - Beam only in the time interval that goes from ~5.8 sec to ~10.4 sec.

- Data processing:
  - FFT of acquired data.
  - Time evolution of FFT
  - Single trace analysis





FFT of acquired data

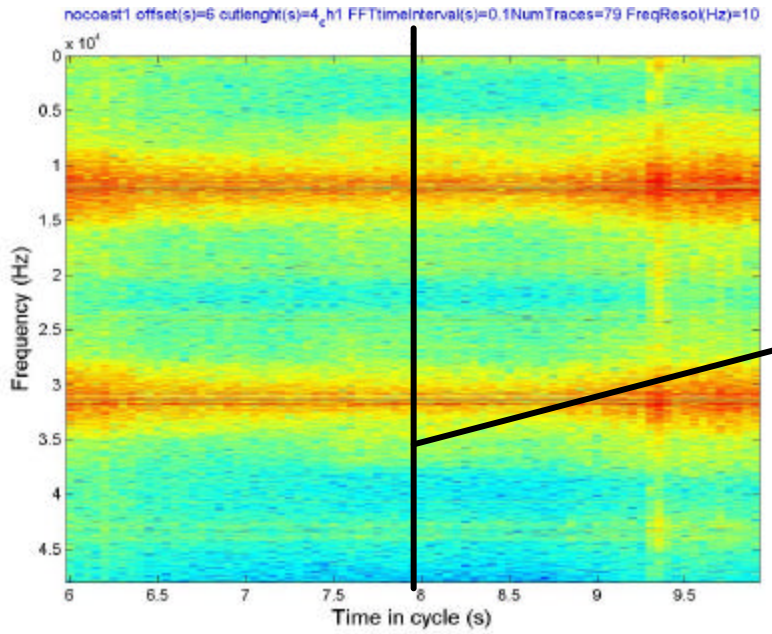
File: nocoast1.wav

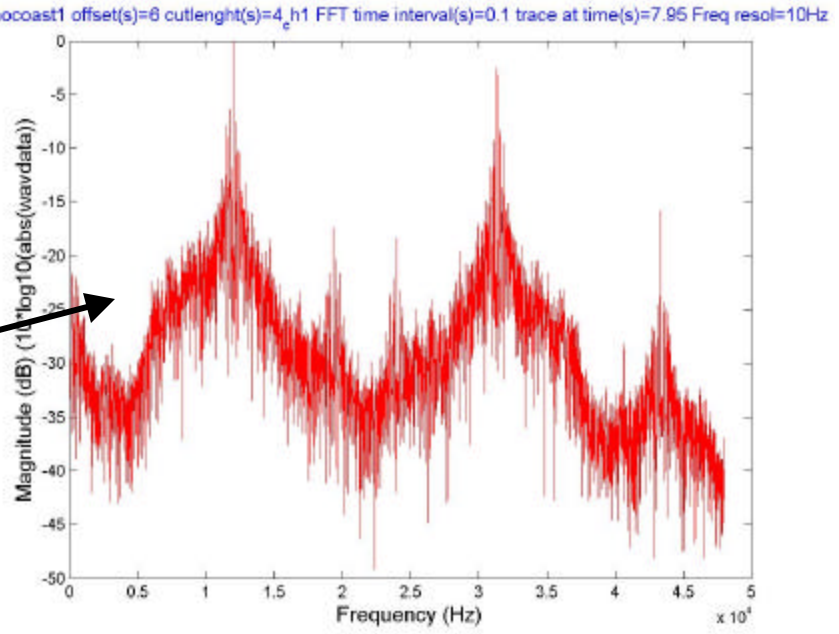
HP 8566B SPA: Center Freq: 1.803 GHz, BW: 30kHz

LO Frequency: 21.40MHz

FFT analysis of time interval 6 – 10 sec. Resolution Freq=10Hz

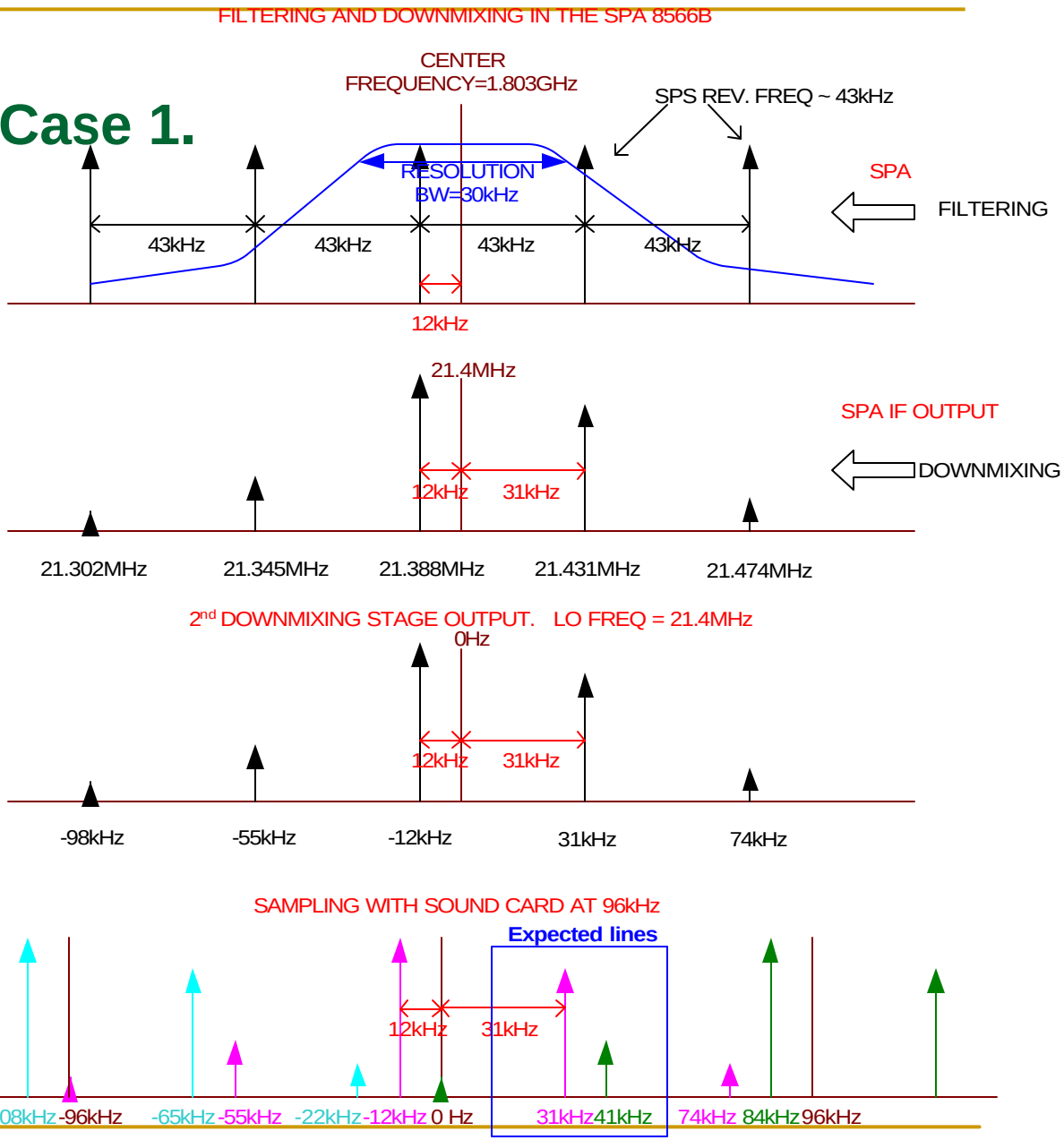
Single trace at time = 7.95 sec





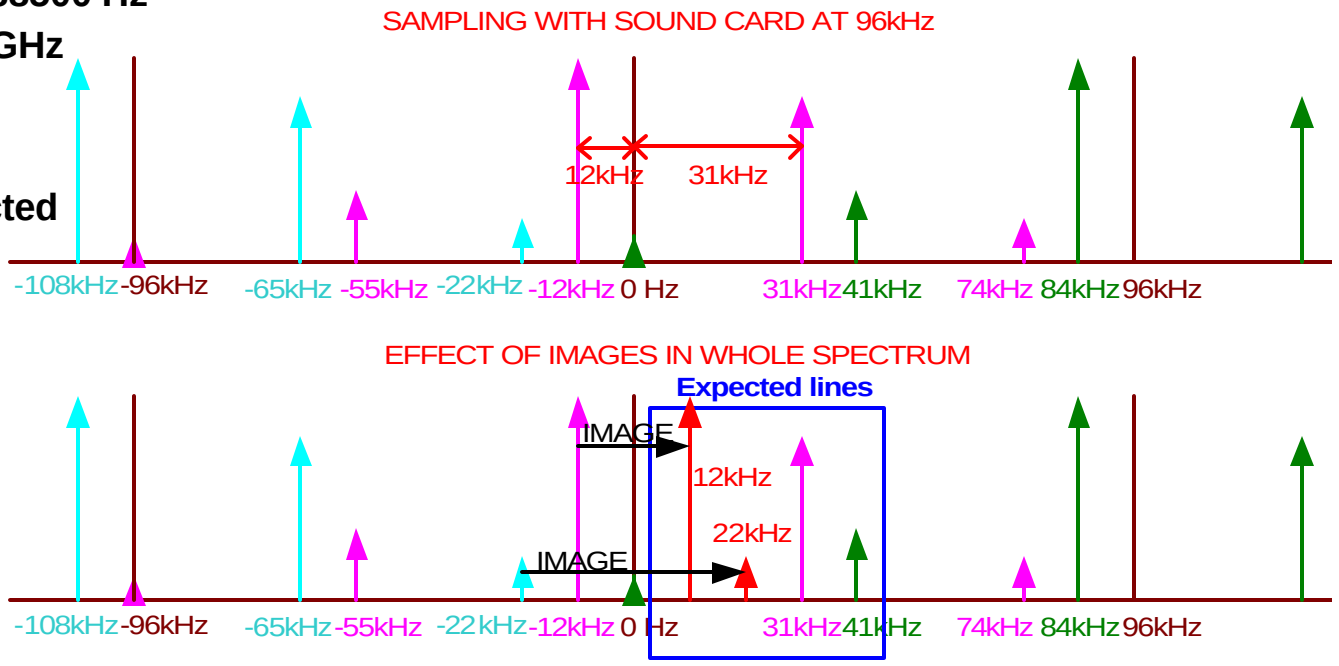
Data analysis. Expected Spectrum. Case 1.

- **Only rev. lines.**
- **LO in 2nd downmixing set to 21.4MHz.**
- **No image effect considered.**
- **No intermodulation or harmonic distortion considered.**
- **PU response at 1802988500 Hz**
- **SPA centered at 1.803GHz**
- **Difference of 11.5kHz (~12kHz)**
- **Two revolution lines expected at ~31 and ~41 kHz.**



Data analysis. Expected Spectrum. Case 1 (cont.).

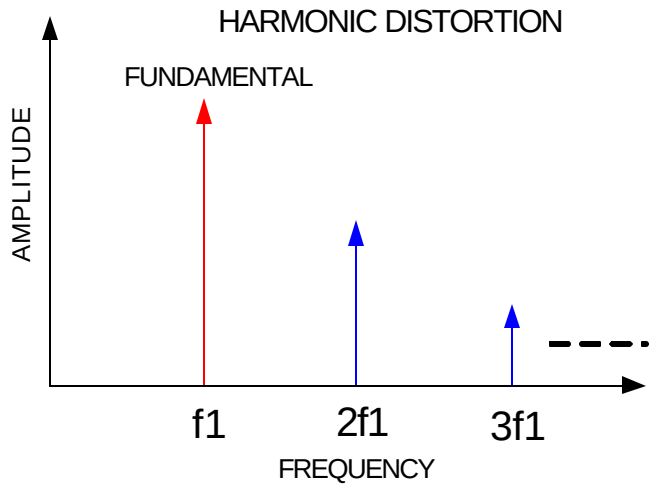
- **Only rev. lines.**
- **LO in 2nd downmixing set to 21.4MHz.**
- **Image effect considered.**
- **No intermodulation or harmonic distortion considered.**
- **PU response at 1802988500 Hz**
- **SPA centered at 1.803GHz**
- **Difference of 11.5kHz (~12kHz)**
- **Revolution lines expected at ~12, ~31 and ~41 kHz.**



Data analysis. Harmonic and Intermodulation distortion.

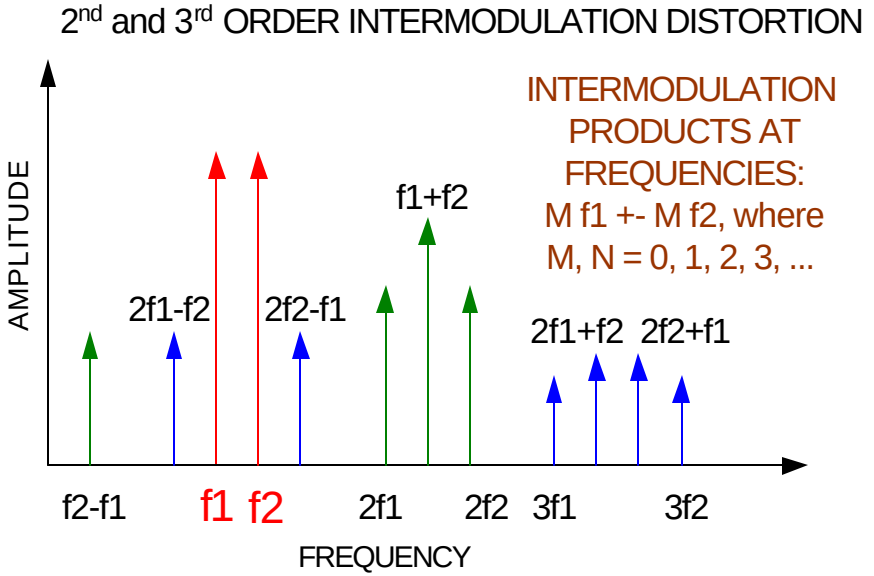
- Harmonic distortion:

Single-tone distortion product caused by nonlinearity of the amplifiers and mixers



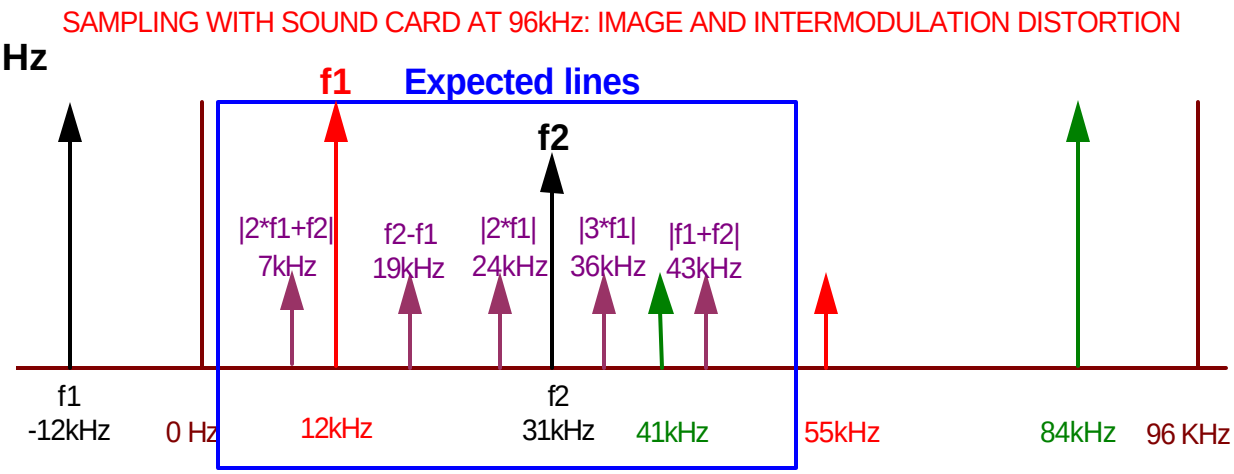
- Intermodulation distortion:

Results when several signals are present at input of non-linear device.



Data analysis. Expected Spectrum. Case 1 (cont.).

- Only rev. lines.
- LO in 2nd downmixing set to 21.4MHz.
- Image effect considered.
- Intermodulation and harmonic distortion considered for the two highest revolution lines.
- PU response at 1802988500 Hz
- SPA centered at 1.803GHz
- Difference of 11.5kHz (~12kHz)
- Revolution lines expected at ~12, ~31 and ~41 kHz.
- Intermodulation products expected at: ~7, ~19, ~24, ~36 and ~43 kHz.
- Peaks @ ~24 and ~36kHz could be also 2nd and 3rd harmonic of rev. Line @ 12kHz.



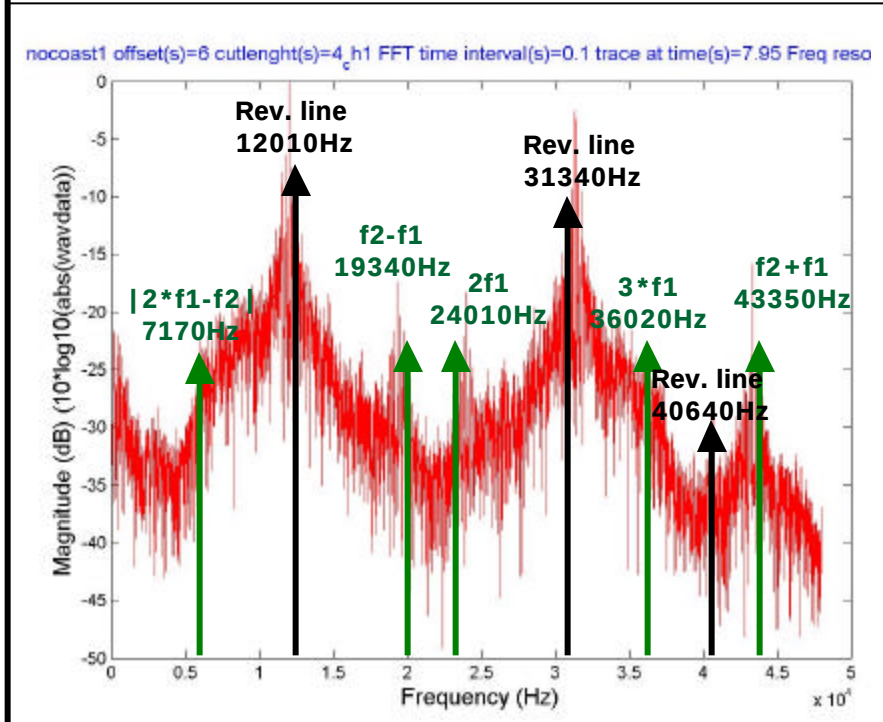
Data analysis. Peaks identification and synchrotron lines.

Revolution lines & harmonic + intermodulation distortion

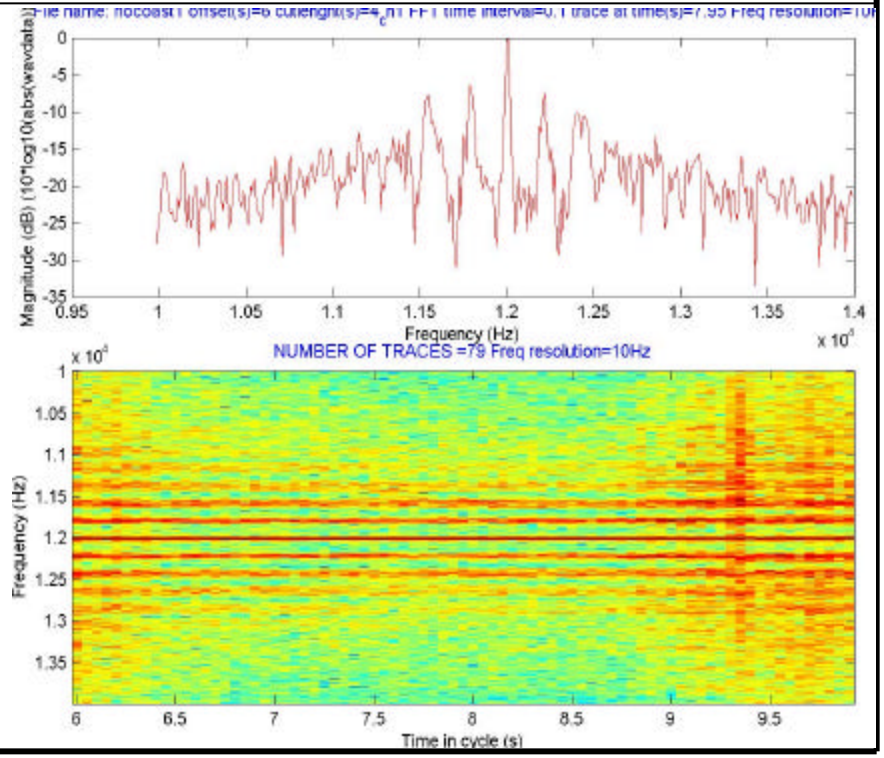
What at first glance seem to be tune lines are in fact intermodulation products!!! No true tune lines visible here.

Peaks identification:

Expected rev lines at ~12, ~22, ~31 and ~41 kHz

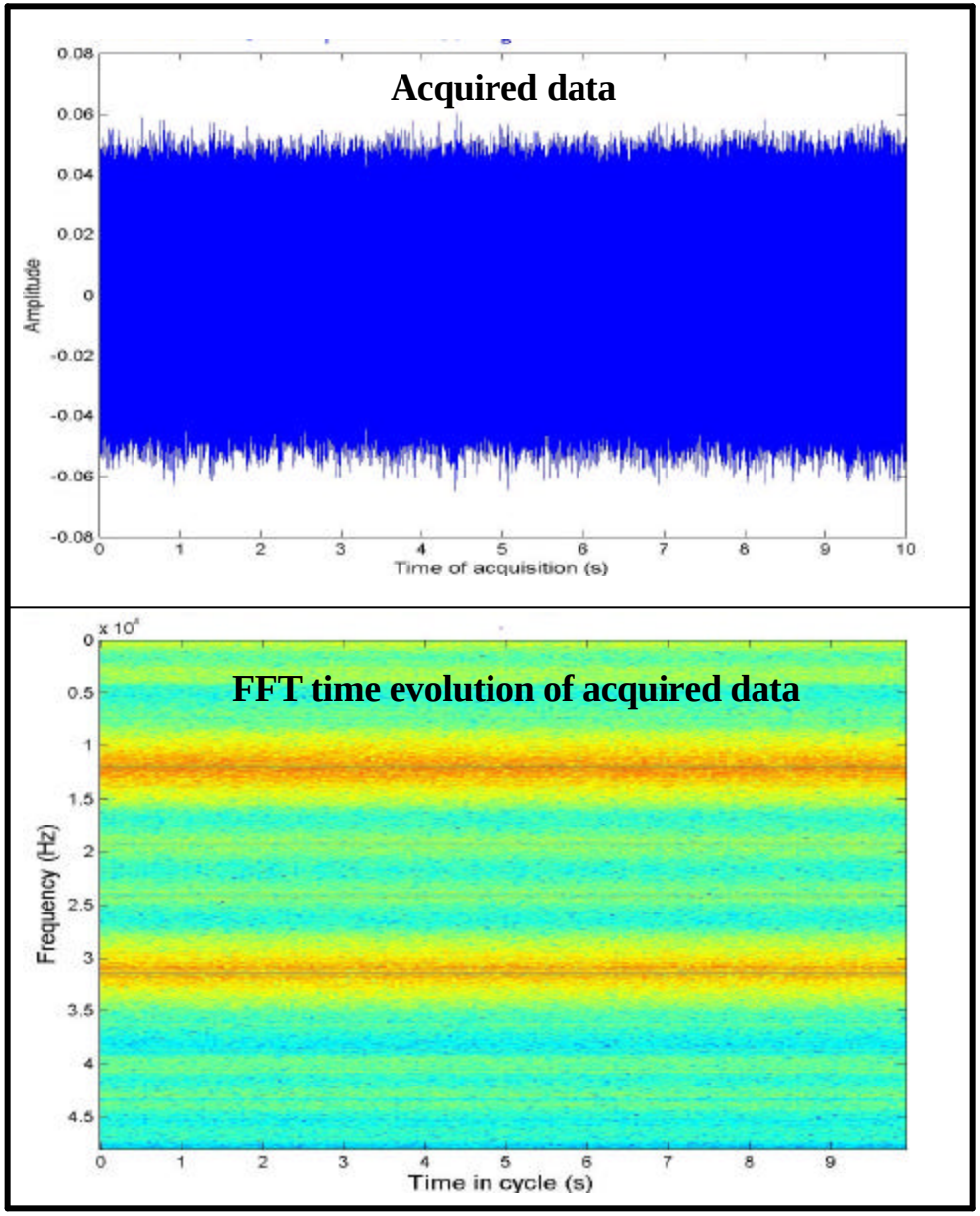


Synchrotron lines around revol. line @ freq=12010 Hz



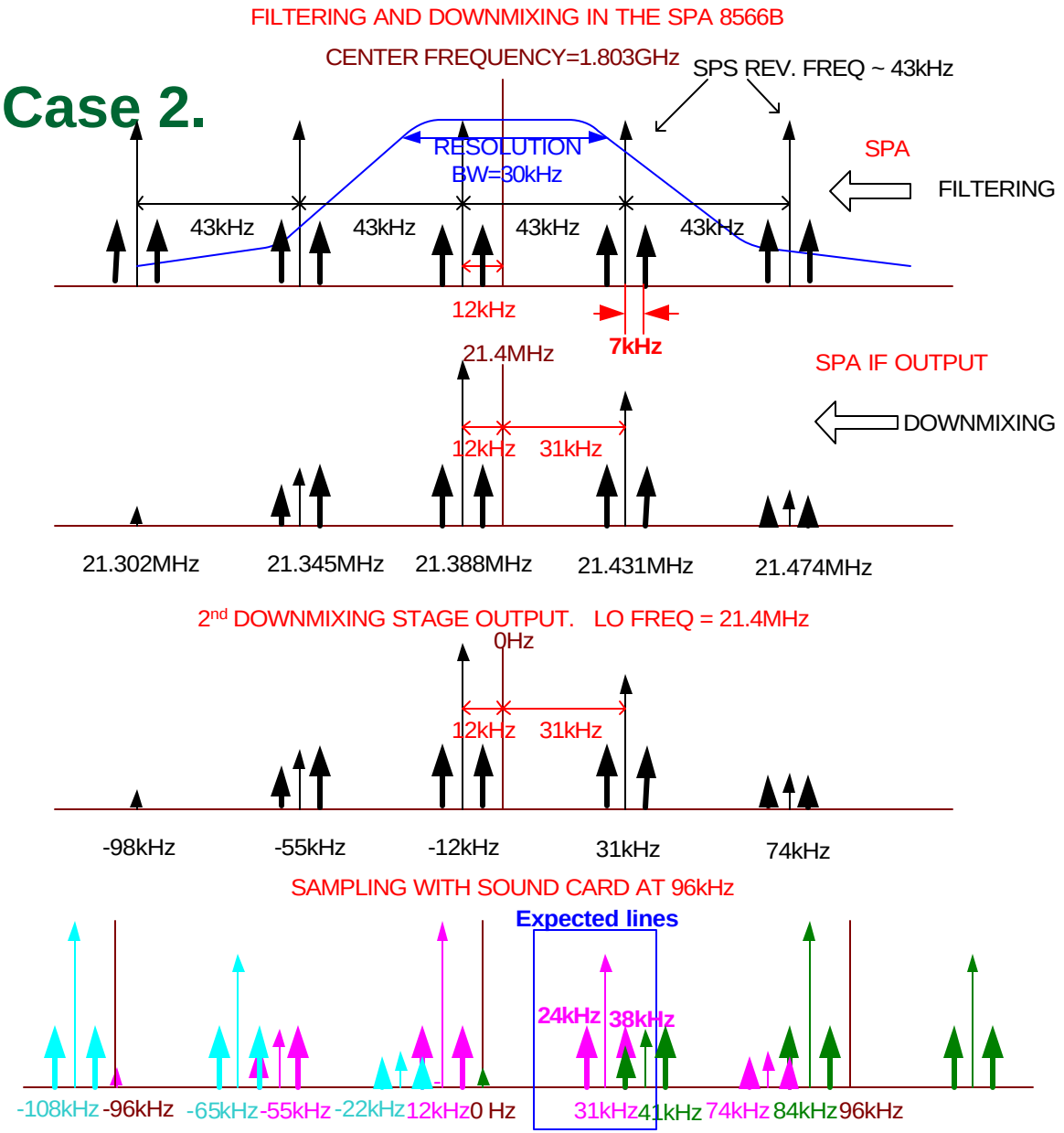
- **Data acquired on 11/11/2004 :**
- Coasting beam.
- Device settings:
  - HP 8566B SPA: Center Freq: 1.803 GHz,

RBW: 30kHz.
  - LO Frequency: 21.40MHz.
- Acquired data:
  - 160 seconds of data.
  - Data analysis in blocks of 10 sec.
- Data processing:
  - FFT of acquired data.
  - Time evolution of FFT.
  - Single trace analysis.



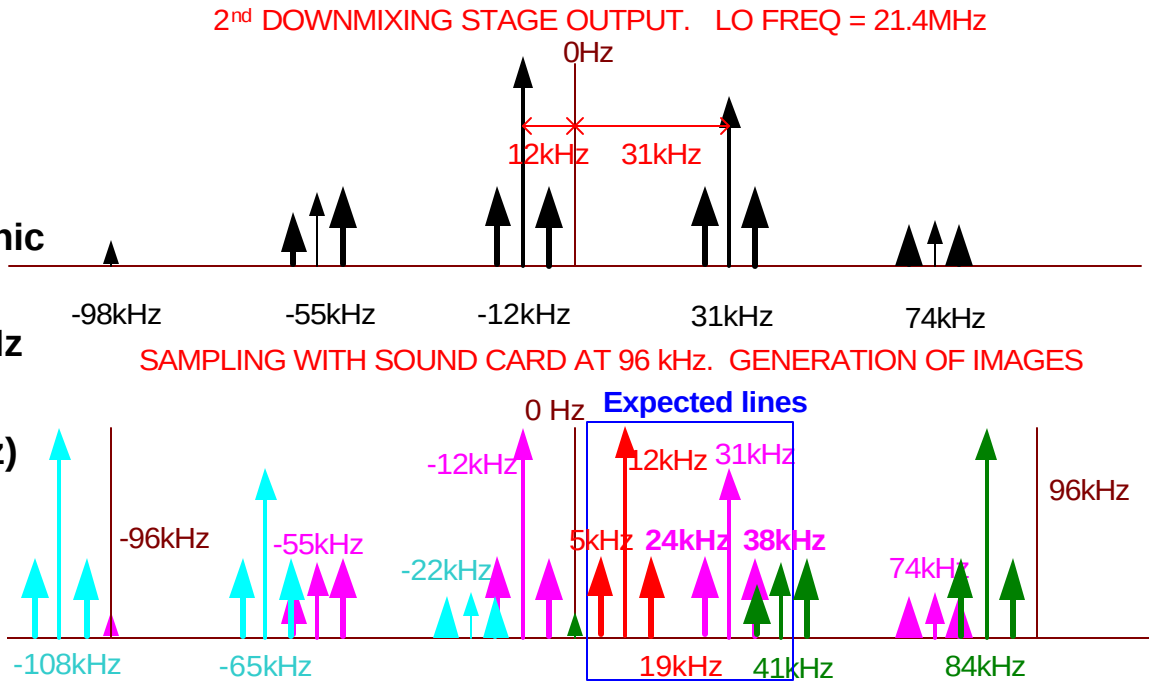
Data analysis.
Expected Spectrum. Case 2.

- **Revolution and tune lines.**
- **LO in 2nd downmixing set to 21.4MHz.**
- **No image effect considered.**
- **No intermodulation or harmonic distortion considered.**
- **PU response at 1802988500 Hz**
- **SPA centered at 1.803GHz**
- **Difference of 11.5kHz (~12kHz)**
- **Revolution lines expected at ~12, ~31 and ~41 kHz.**
- **Tune lines expected at ~24 and ~38 kHz.**



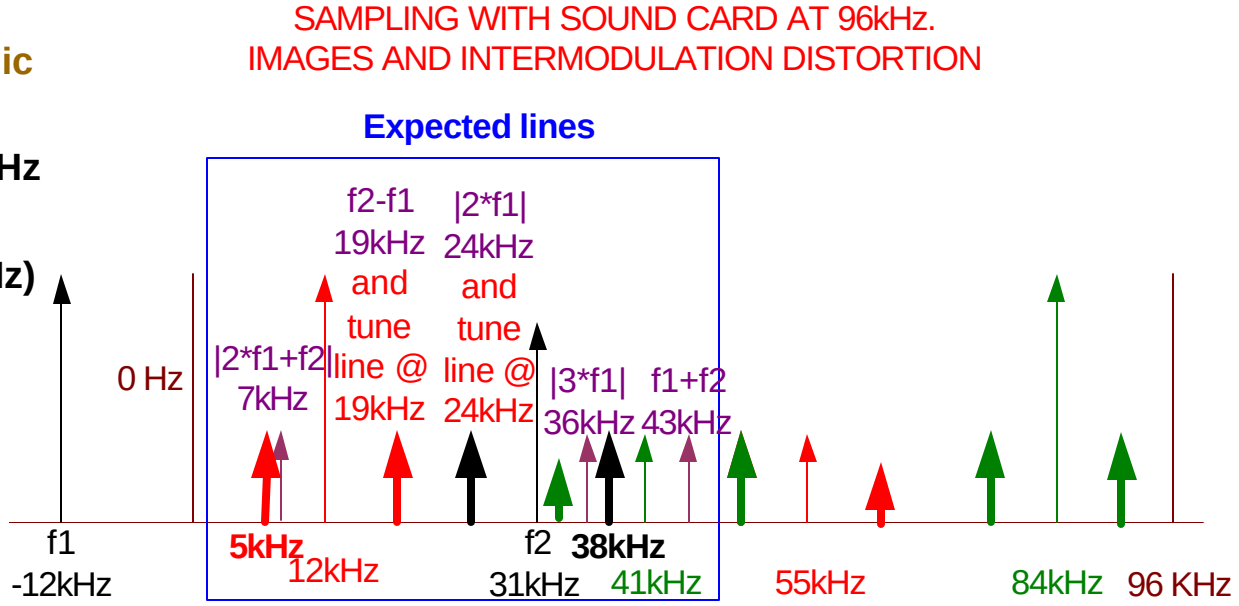
Data analysis. Expected Spectrum. Case 2 (cont.).

- **Revolution and tune lines.**
- **LO in 2nd downmixing set to 21.4MHz.**
- **Image effect considered.**
- **No intermodulation or harmonic distortion considered.**
- **PU response at 1802988500 Hz**
- **SPA centered at 1.803GHz**
- **Difference of 11.5kHz (~12kHz)**
- **Revolution lines expected at ~12, ~31 and ~41 kHz.**
- **Tune lines expected at ~5, ~19, ~24 and ~38 kHz.**



Data analysis. Expected Spectrum. Case 2 (cont.).

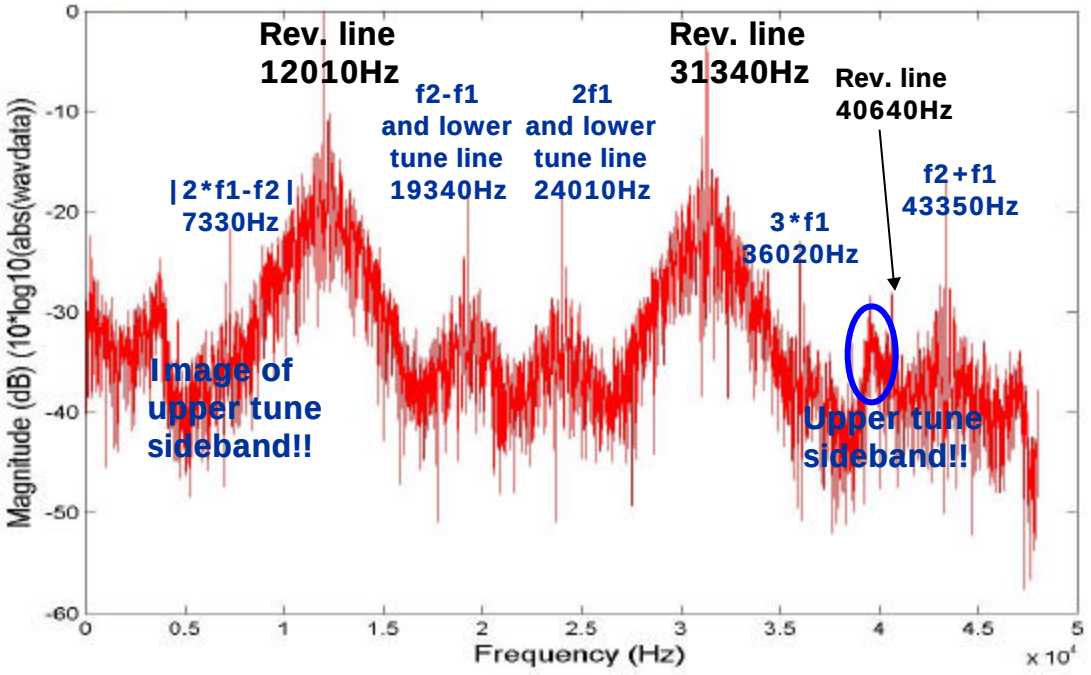
- **Revolution and tune lines.**
- **LO in 2nd downmixing set to 21.4MHz.**
- **Image effect considered.**
- **Intermodulation and harmonic distortion considered.**
- **PU response at 1802988500 Hz**
- **SPA centered at 1.803GHz**
- **Difference of 11.5kHz (~12kHz)**
- **Revolution lines expected at ~12, ~31 and ~41 kHz.**
- **Tune lines expected at ~5, ~19, ~24 and ~38 kHz.**
- **Intermodulation products expected at: ~7, ~19, ~24, ~36 and ~43 kHz.**



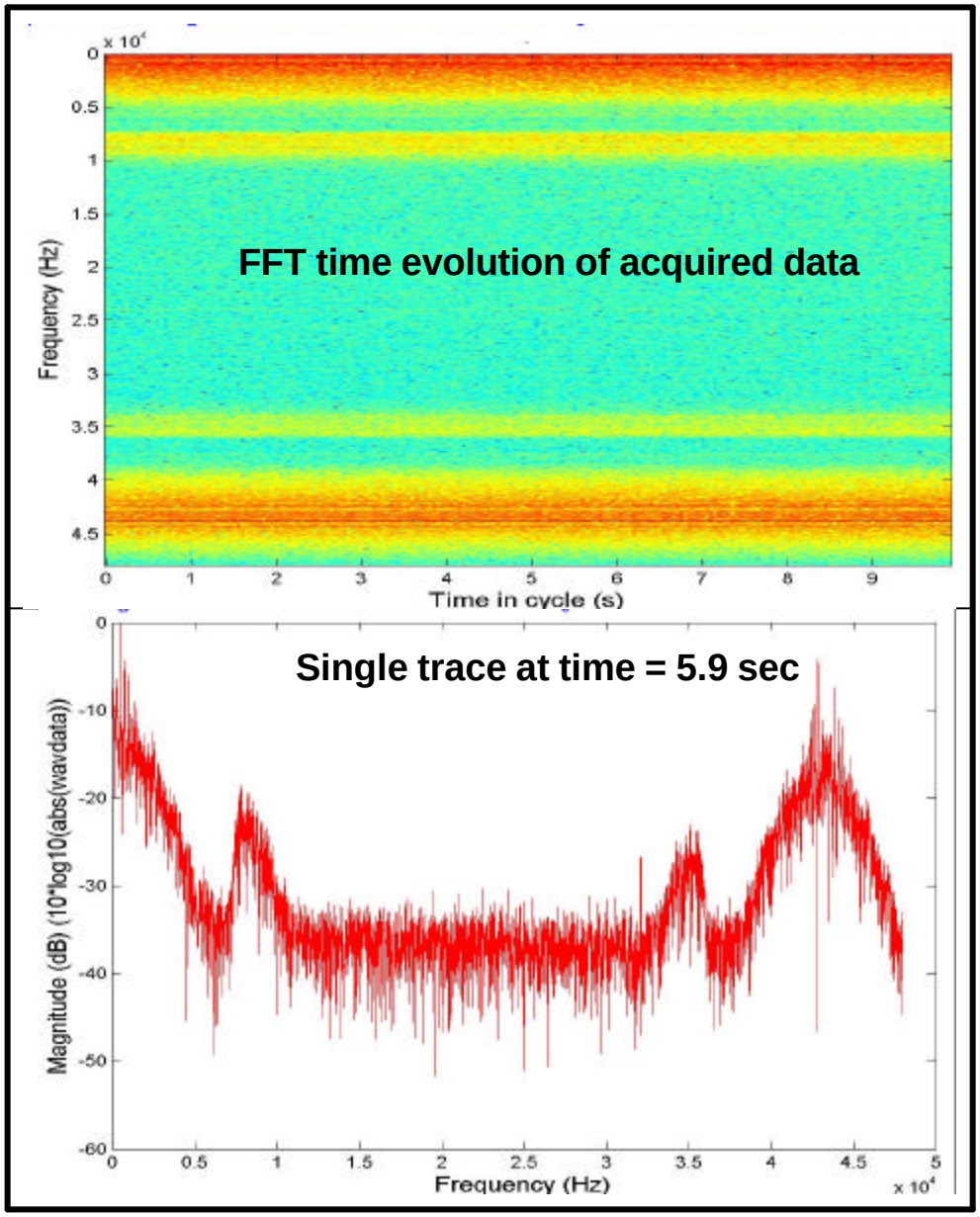
Data analysis. Peaks identification.

Revolution lines expected @ ~12kHz and ~31kHz

At the time of data acquisition tune value is 0.175➔ tune lines @~0.175*43.374kHz=7.586kHz below and above the rev. line
Two peaks at about that distance appear in the spectrum. They are the lower sidebands, overlapping with harmonic distortion products??
Upper sideband peaks could be buried in noise

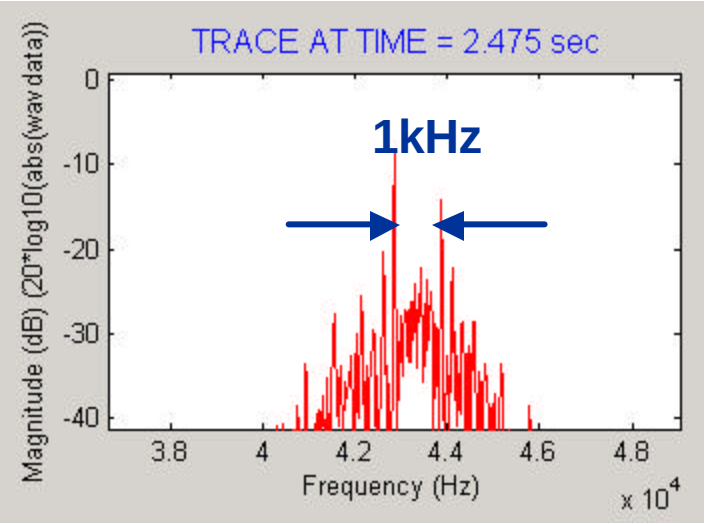


- **Data acquired on 11/11/2004**
- Coasting beam.
- Device settings:
  - HP 8566B SPA: Center Freq: 1.8029885 GHz, RBW: 30kHz.
  - LO Frequency: 21.40MHz.
- Acquired data:
  - 140 seconds of data.
  - Data analysis in blocks of 10 sec.
- Data processing:
  - FFT of acquired data.
  - Time evolution of FFT.
  - Single trace analysis.



Data analysis:

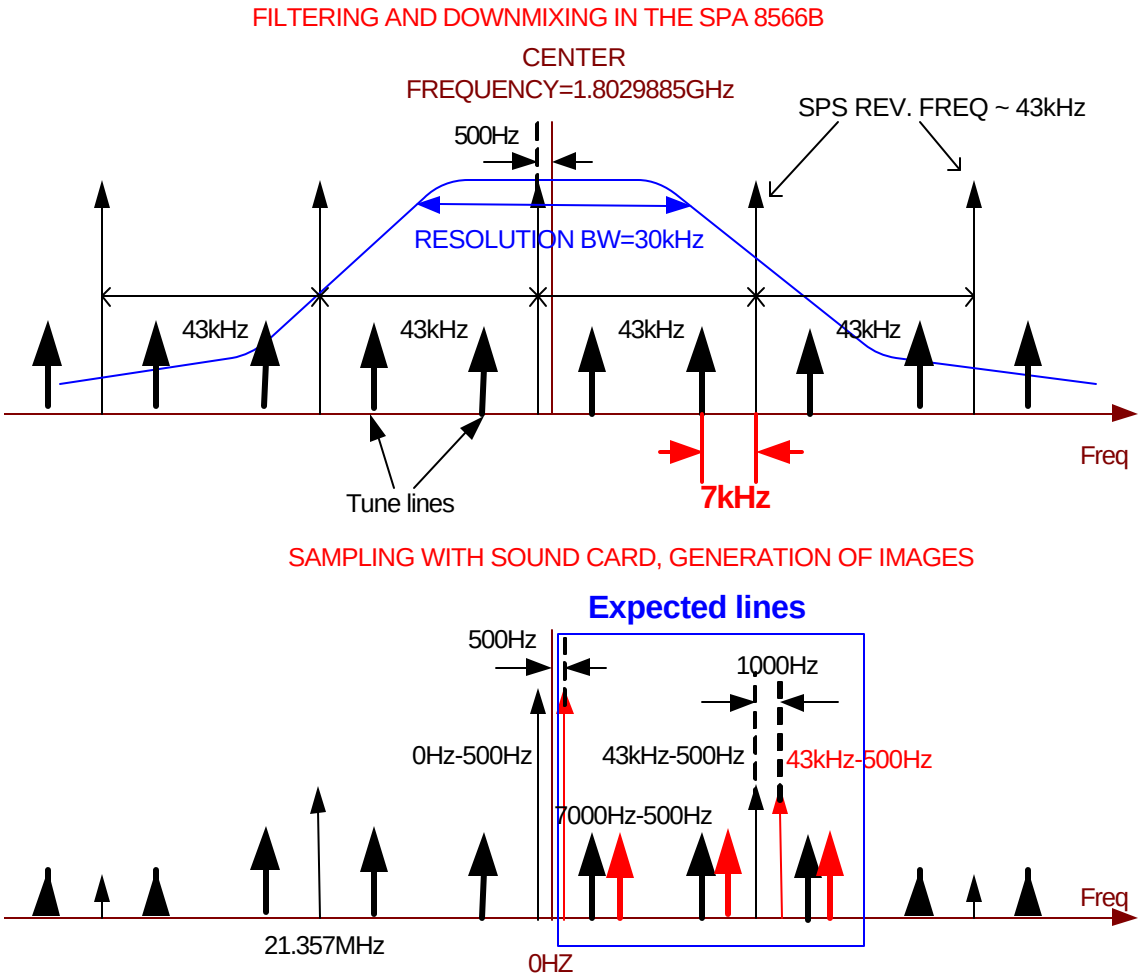
- PU response at 1802988500 Hz and SPA filter centered at 1.802988500GHz.
- Two revolution lines are observed at ~0 Hz and ~43kHz. However, a close view on the 43kHz peak shows that in fact there are two peaks spaced by ~1kHz ➔ This points towards an overlap of the signal spectrum and its image spectrum.



- The 1kHz difference comes from an offset of ~500Hz in the center frequency of the SPA with respect to the PU response, an error coming from the fact that the revolution harmonic frequency was measured with a SPA different from the one used for the actual down conversion. The two SPA were not phase locked and so their frequency bases were offset.

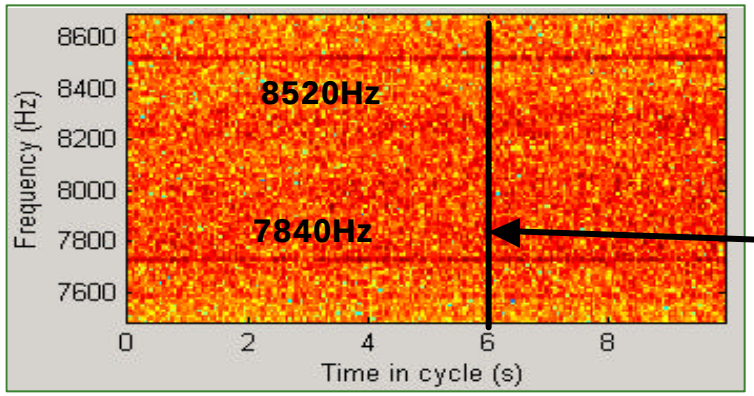
Data analysis. Expected Spectrum. Case 3.

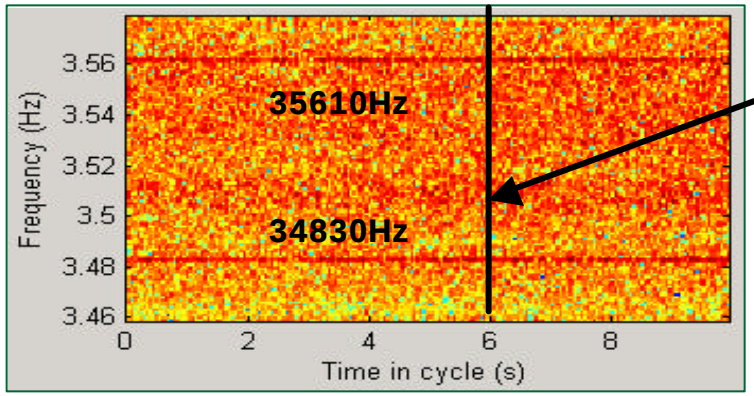
- **Revolution and tune lines.**
- **LO in 2nd downmixing set to 21.4MHz.**
- **Image effect considered.**
- **No intermodulation or harmonic distortion considered.**
- **PU response at 1802988500 Hz**
- **SPA centered at 1802988500 Hz**
- **Assumption of error in SPA center frequency of 500Hz.**
- **Revolution lines expected at ~0 and ~43 kHz.**
- **Tune lines expected at ~7 kHz and ~36 kHz.**

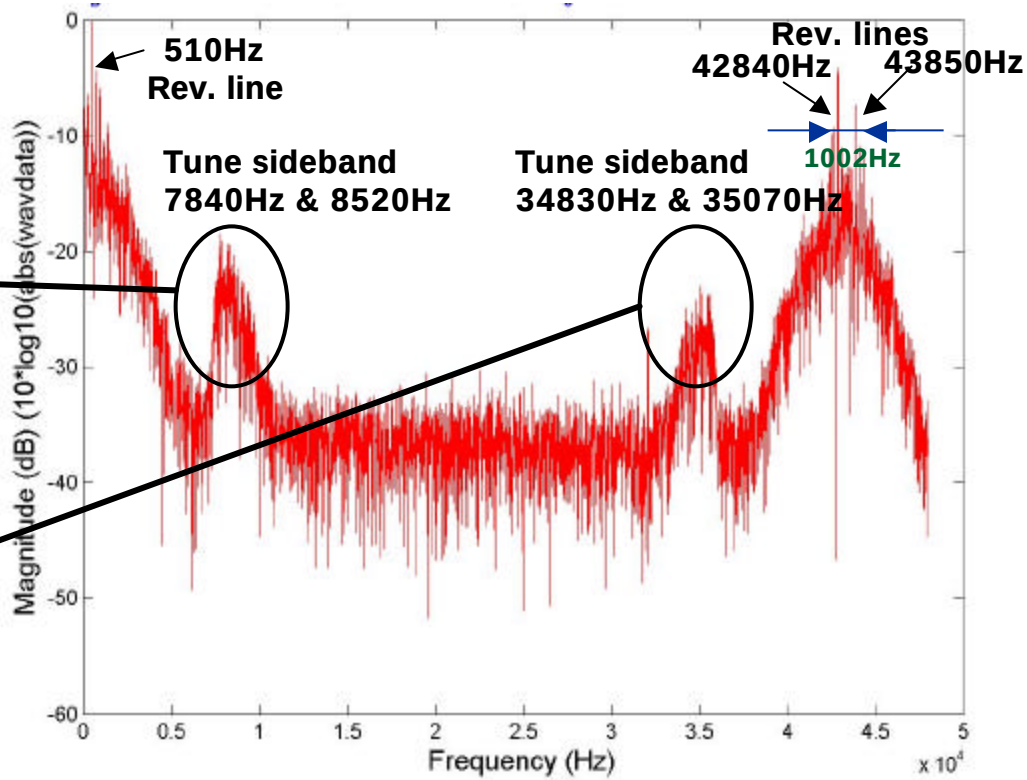


Data analysis. Peaks identification.

-Two main peaks @ ~ 0Hz and 43kHz.
-Close look: two peaks spaced by ~1kHz
-Tune lines expected @ ~7.5kHz and ~32kHz. -Overlap of two spectrums displaced by 1002Hz.

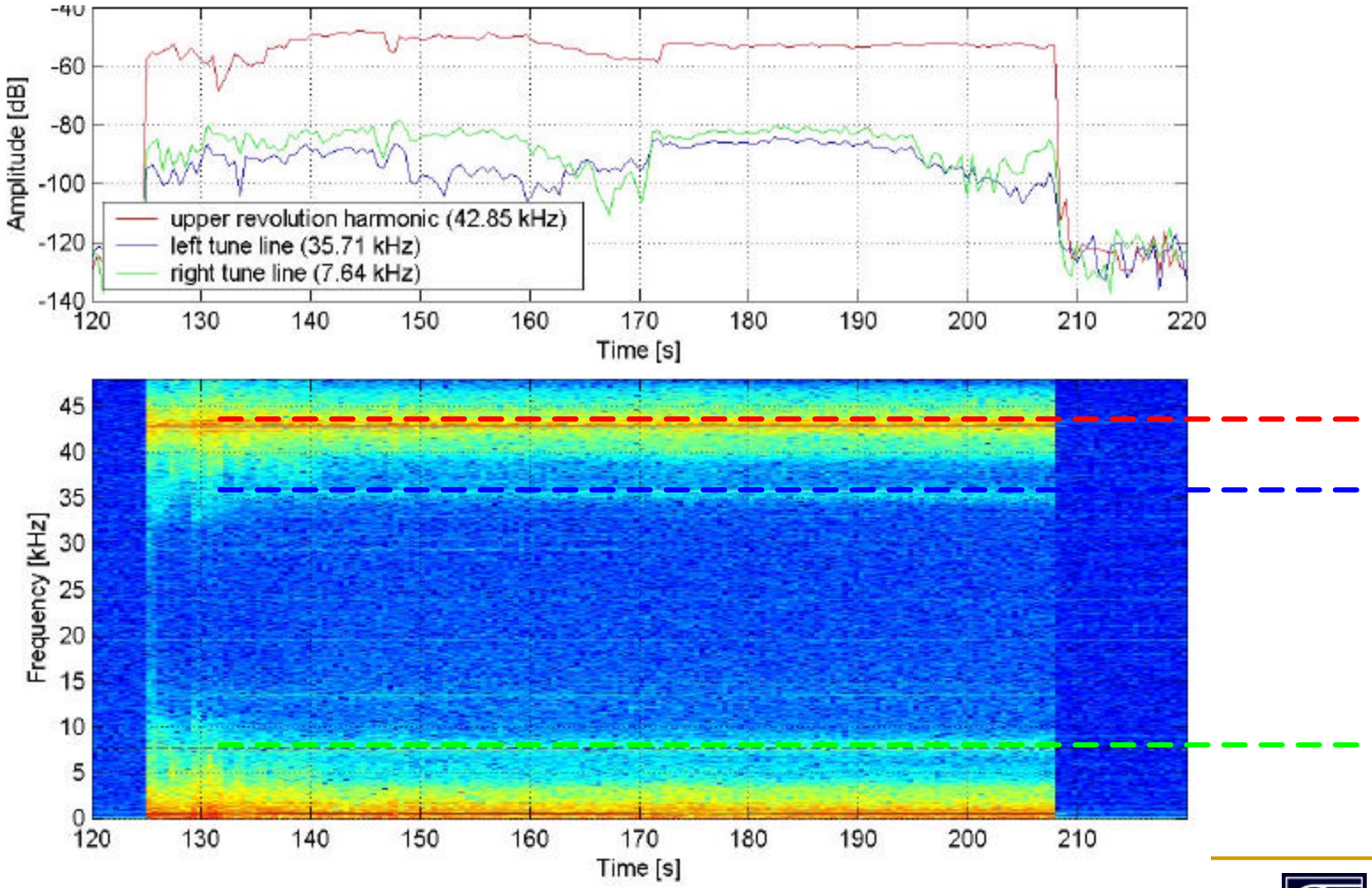






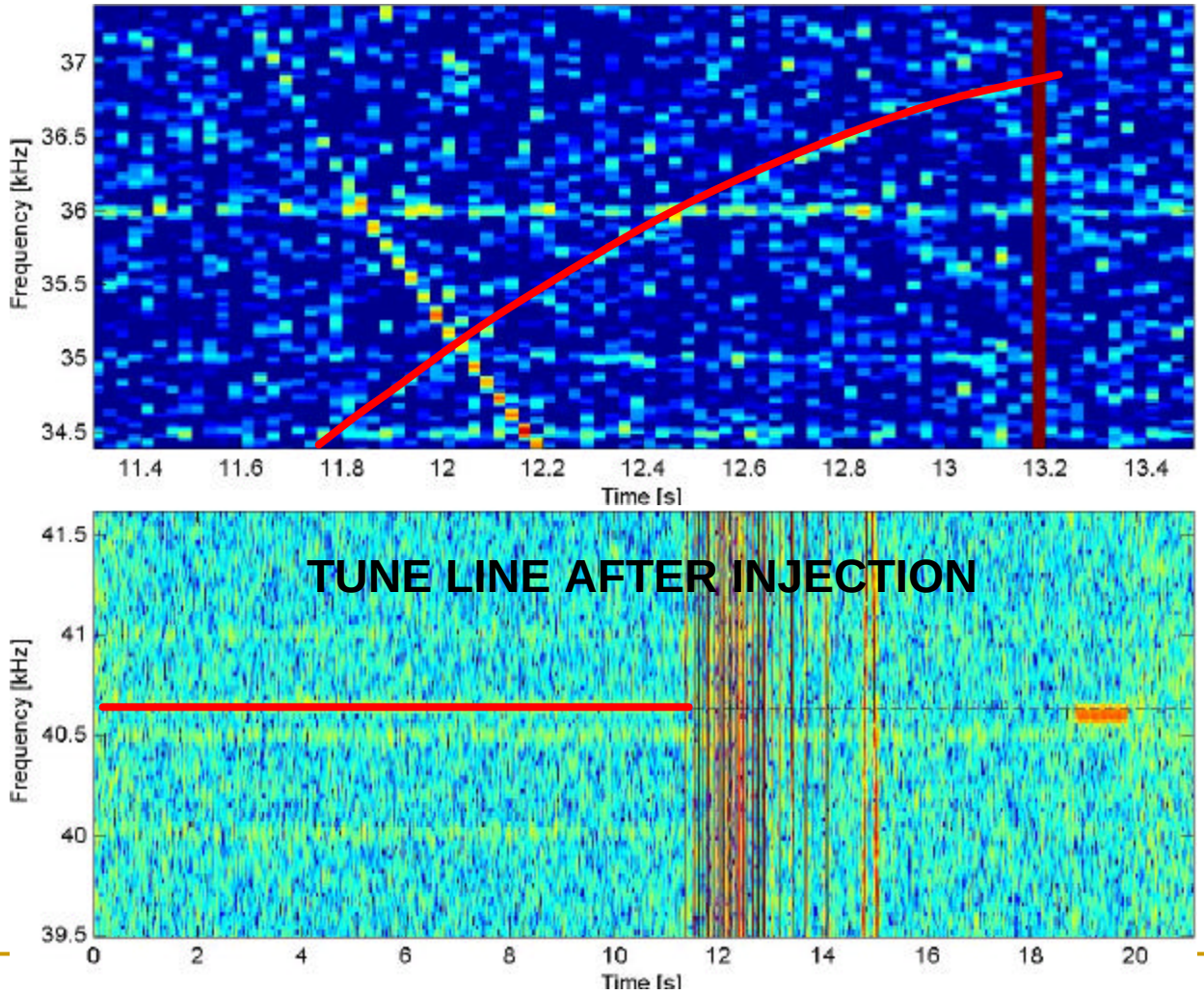
Data analysis. Long time behaviour

Long trace on a coast over about 100 s. The harmonic is pretty wide within the first 15 s, then get narrower. The upper plot shows the evolution of one harmonic line and two coherent tune lines versus time.



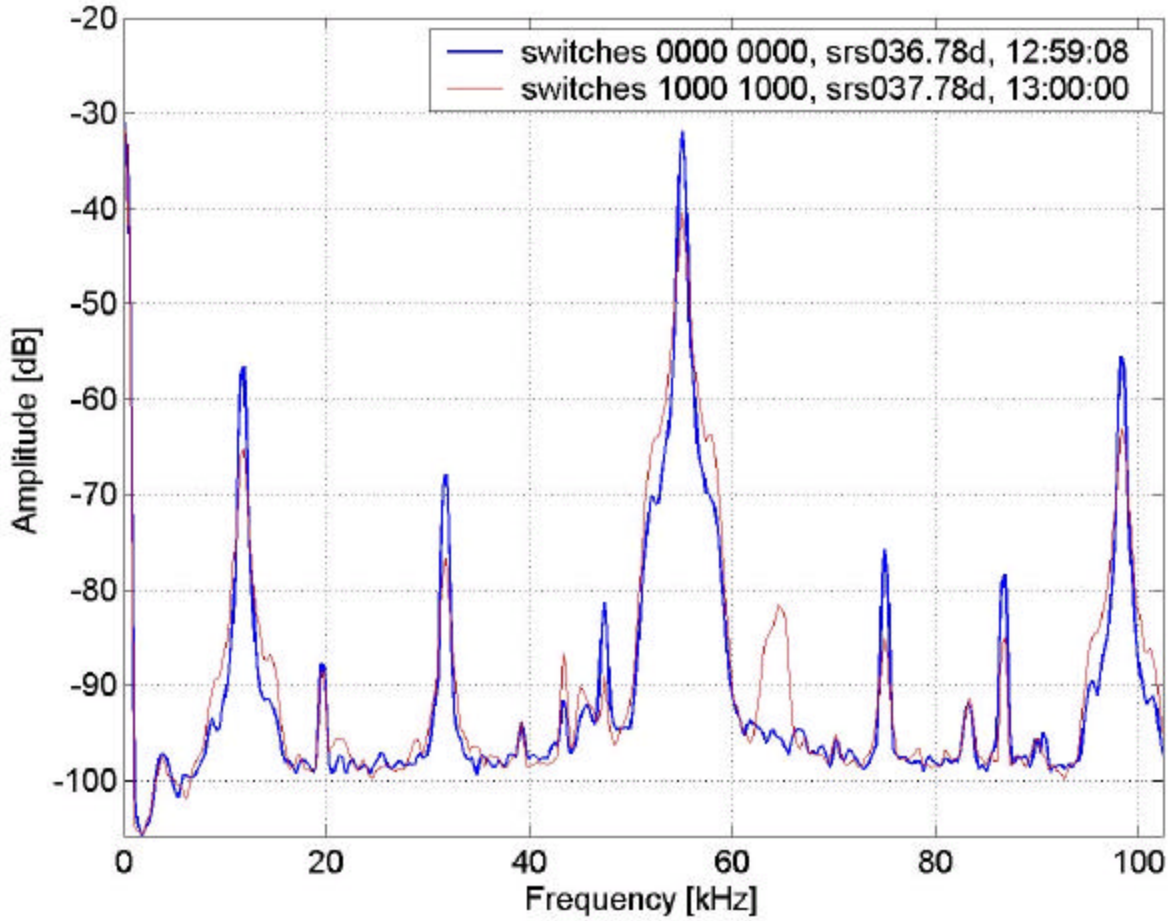
Data analysis. Pilot beam

- Single pilot bunch with nominal intensity $5*10^9$ p.
- Faint trace of a tune line with a priori knowledge of expected value. However, we do not claim that this tune is exclusively incoherent.



Data analysis. Switches upstream of combiner hybrid

Example of the impact of the switches setting. A potential suppression of the harmonics by about 8 dB was found...



CONCLUSIONS…

- We could clearly see vertical tune sidebands for different beams from the 1.7-1.8GHz PU in BA5.
- We have done and extensive signal analysis for static and dynamic beam conditions including identification of harmonics, images and intermodulation products.
- We have seen strong longitudinal and faint transverse signals of pilot beams ($5*10^9$ p, single bunch) at minimum and maximum momentum without gating.
- For certain beams a maximum voltage of about 100 V peak to peak was found in the sum output of the hybrid.

Acknowledgments:

This work would not have been possible without the patient and continuous flow of information of Ralph Pasquinelli from Fermilab, including all the detailed mechanical drawings for the structure.
BDI Group, in particular J.P. Koutchouk, H. Schmickler and Rhodri Jones for support, as well as Trevor Linnecar and F. Pedersen from the RF Group.
Jacques Genest and Gerard Burtin, Claude Fischer and the RF group mechanical workshop for preparing and organizing a big part of the mechanical work.
Gerard Tranquille for contributing to the theoretical analysis, Jean-Francois Malo for help and all the others we have not mentioned here...